

# **Seal Technology for Hypersonic Vehicle and Propulsion: An Overview**

## **Abstract**

Hypersonic vehicles and propulsion systems pose an extraordinary challenge for structures and materials. Airframes and engines require lightweight, high-temperature materials and structural configurations that can withstand the extreme environment of hypersonic flight.

Some of the challenges posed include very high temperatures, heating of the whole vehicle, steady-state and transient localized heating from shock waves, high aerodynamic loads, high fluctuating pressure loads, potential for severe flutter, vibration, and acoustic loads and erosion. Correspondingly high temperature seals are required to meet these aggressive requirements.

This presentation reviews relevant seal technology for both heritage (e.g. Space Shuttle, X-15, and X-38) vehicles and presents several seal case studies aimed at providing lessons learned for future hypersonic vehicle seal development. This presentation also reviews seal technology developed for the National Aerospace Plane propulsion systems and presents several seal case studies aimed at providing lessons learned for future hypersonic propulsion seal development.

# **Seal Technology for Hypersonic Vehicles and Propulsion Systems: An Overview**

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## **Short Course on**

## **Hypersonics**

## **Structures and Materials**

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**National Institute of Aerospace**

**Hampton, VA**



## Section 8.4.4.2: Vehicle Seals



**Space Shuttle**



**X-15: First Piloted Hypersonic Aircraft**



**X-38 Test Vehicle**



**Future Hypersonic Vehicles**

# Outline

- Vehicle Seal Locations
- Hypersonics Challenge: Materials and Structures Perspective
- Heritage Vehicles:
  - X-15
    - Canopy seal failure, nose landing gear door seal failure, control surface seals
  - Shuttle:
    - Overview, gap filler designs, elevon cove seal, main landing gear door seals
- Performance criteria for high temperature seals
  - Establishing vehicle seal design requirements
  - Challenges for advanced airframe thermal barriers
- Test capabilities to evaluate advanced seal concepts
  - General roadmap
  - Test rigs: compression, scrub, flow
  - Arc jet tests
- Seal performance assessments
  - Case Study 1: Shuttle environmental seal: load, flow,
  - Case Study 2: Thermal barrier: compression, resiliency, flow, arc jet
- Summary
- Future work
- References (end of package)



# Vehicle Seal Locations

## Control Surfaces:

- Rudders
- Elevons
- Body Flap

## Vehicle TPS

- Leading edges
- Gaps/seams
- Engine/Airframe Interface



## Vehicle Penetrations:

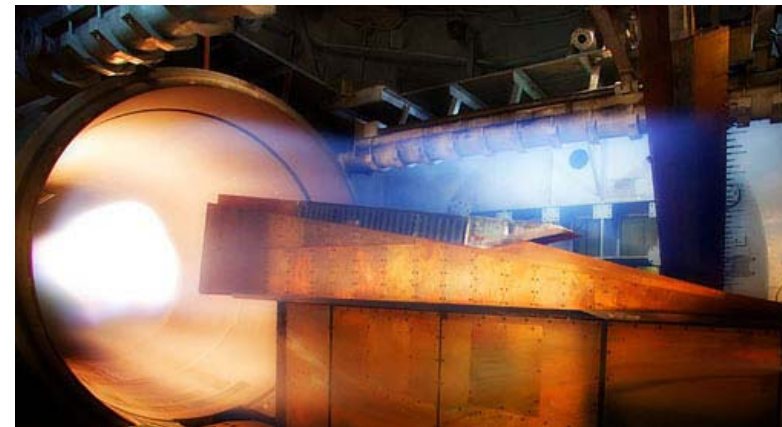
- Landing gear doors
- Cargo bay doors
- Payload bay doors
- Crew access doors
- Canopy

# Hypersonics Challenge: Materials and Structures Perspective

- Hypersonic vehicles an extraordinary challenge for structures and materials.
- Airframe and engine require lightweight, high-temperature materials and structural configurations that can withstand the extreme environment of hypersonic flight:
  - Very high temperatures
  - Heating of the whole vehicle
  - Steady-state and transient localized heating from shock waves
  - High aerodynamic loads
  - High fluctuating pressure loads
  - Potential for severe flutter, vibration, and acoustic loads.
  - Erosion from airflow over the vehicle and through the engine



**Large scale panel/pylon test in Ames IHF**



**X-51 Engine Test at Mach 5 in LaRC Tunnel**

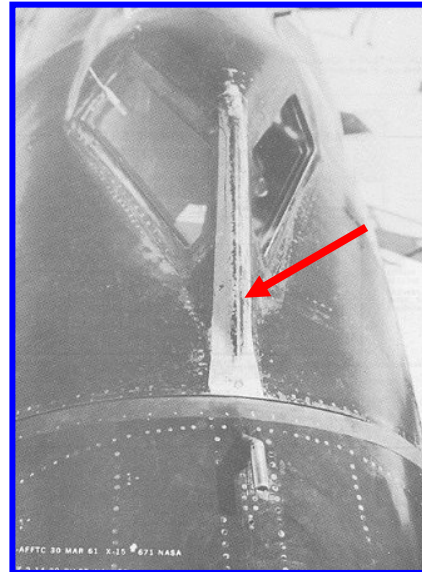
# X-15 Seal Experiences - Abridged

## Canopy Seal

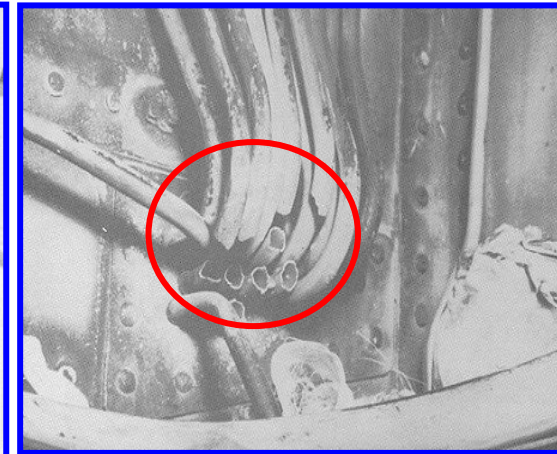
- Program's first "hands-on" awareness of the effects of aerodynamic heating
  - Mach 3+ flight, "-11" engine".
- Canopy lifted slightly at the front edge (due to differential pressure at altitude)
  - Stagnation air burned rubber canopy seal → loss of cabin pressure.
- Fix: Narrow Inconel deflector strip limiting heat to seal location

## Nose Landing Gear Door Seal

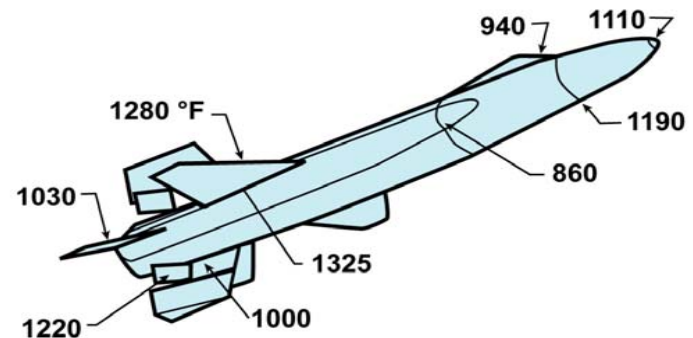
- Small gap in the nose wheel door seal allowed torch-like stream of hot boundary layer gas to enter the wheel well. (Mach 4.5)
  - Aluminum instrumentation pressure lines in the nose-wheel well were observed to be melted and severed.
  - Paint on the bulkhead behind the tubes (a cockpit pressure bulkhead) was badly burned and scorched
    - Bulkhead remained undamaged.



Canopy



Nose-Wheel Well  
Instrumentation Damage



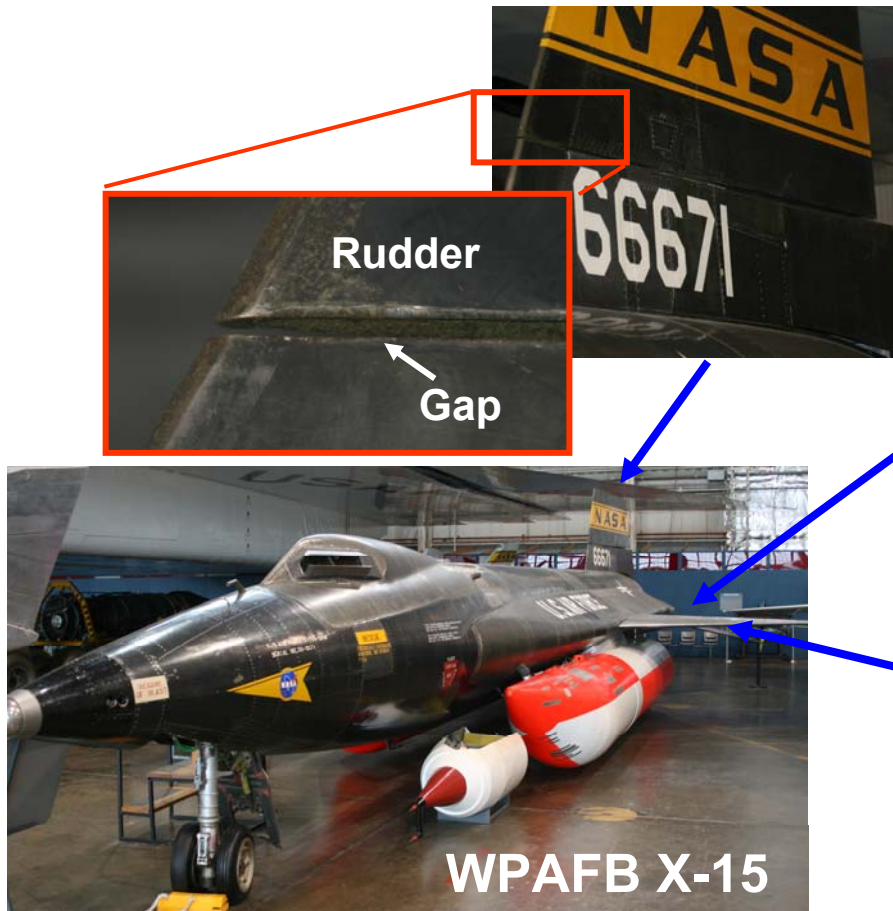
Measured temperatures in flight at Mach 5

Canopy Seal Ref: Robert G. Hoey  
[www.hq.nasa.gov/pao/History/x15conf/contrib.html](http://www.hq.nasa.gov/pao/History/x15conf/contrib.html)

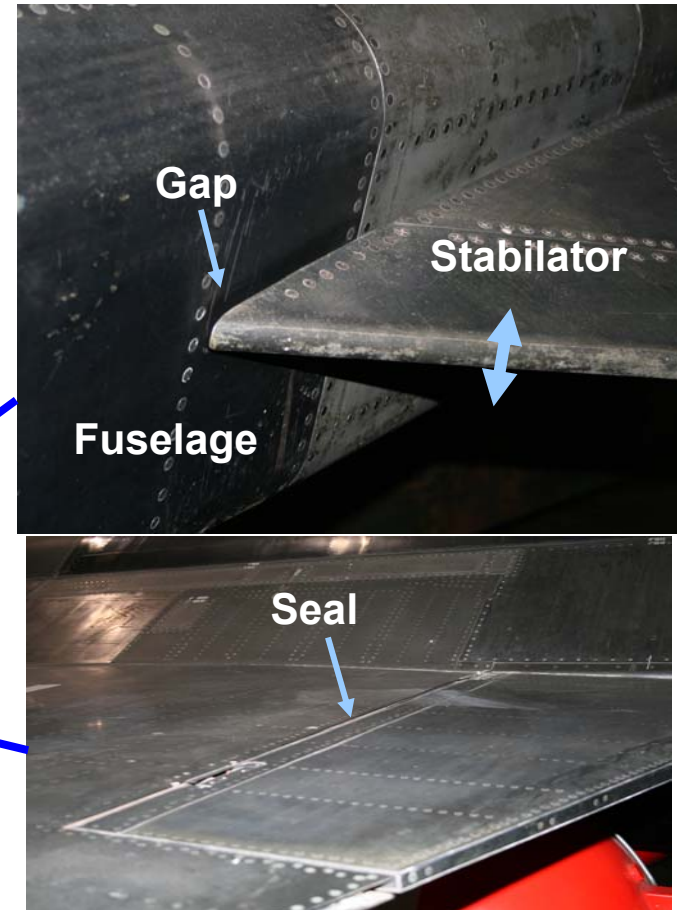
# X-15 Control Surfaces:

## Close-up photos of seal locations

**Rudder (Full motion):** Controlled Yaw  
Seal: Clearance gap, external  
(Perhaps internal rotary seal on hinge)



**Stabilators:** Controlled Pitch/Roll  
Seal: Clearance gap, external



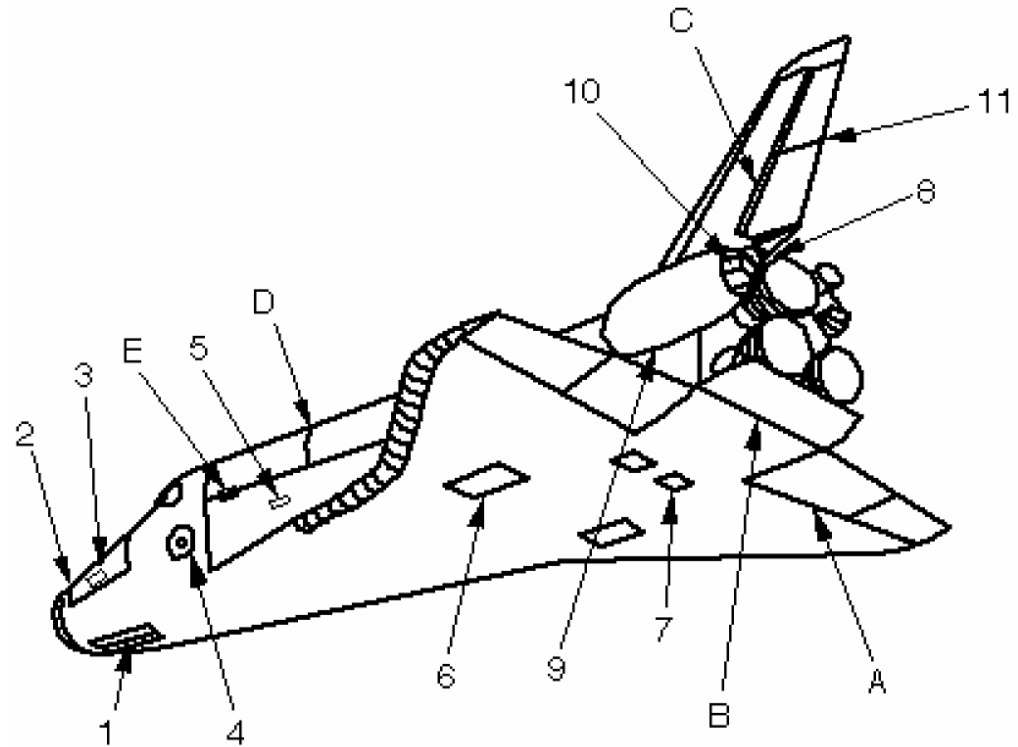
**Left Flap:** Additional Lift during glide  
Seal: Black elastomeric tube (fluorocarbon?)



# Shuttle Thermal Barrier & Aero-thermal Seal Locations

## Thermal Barriers

1. Nose Landing Gear Door
2. FRCS Module/Fuselage Interface
3. Forward RCS Thrusters
4. Crew Hatch
5. Vent Doors
6. Main Landing Gear Doors
7. External Tank Doors
8. Vertical Stabilizer/Fuselage Interface
9. OMS Pod/Fuselage Interface
10. OMS Pod RCS Thrusters
11. Rudder Speed Brake Split Line



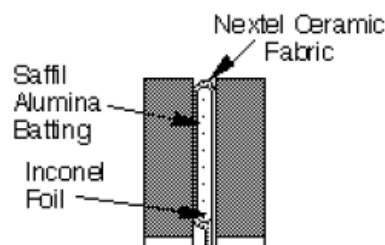
## Aero-thermal Seals

- A. Wing/Elevon
- B. Aft Fuselage/Body Flap
- C. Vertical Stabilizer/Rudder Speed Brake
- D. Payload Bay Door Expansion Joint
- E. Payload Bay Door Hinge Covers

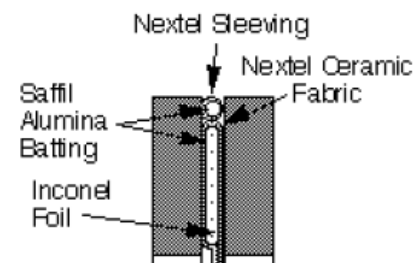
Ref: C. Snapp, Report KLO-00-006, October 17, 2000

# Shuttle Gap Fillers

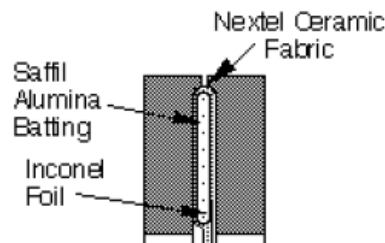
- Gap fillers are used to restrict the flow of hot gas into the gaps of TPS components.
  - Prevent overheating of aluminum structure
  - Prevent “gap-heating”
- Predominant gap filler types used are:
  - Pillow or pad type
  - Ames type.
- Materials
  - Foil: Inconel 601
  - Ceramic Overwrap: Nextel 312
  - Batting: Alumina (Saffil)
  - Stitching Thread: Nextel 312
  - Tail stiffened and also bonded to underlying filler bar or tile sidewall with RTV
- High Emissivity Coating:
  - Two Step process including
    - Precoat: Ludox ammonia stabilized colloidal silica solution, isopropyl alcohol, and bal. silicon carbide powder
    - Top Coat: Ludox ammonia stabilized colloidal silica solution, silica powder, silicon carbide powder applied to the exposed area of the gap filler



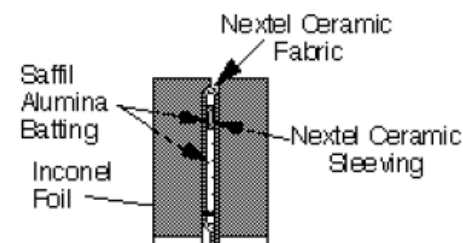
Pillow or Pad Type



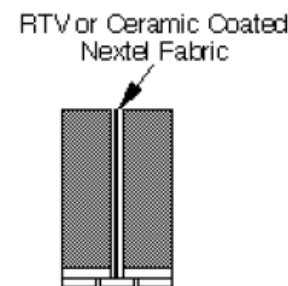
Pillow With Sleeveing



Pillow Captive Type  
(Double Lip)



Pillow Captive Type  
(Single Lip)



Ames Type

TPS: Thermal Protection System

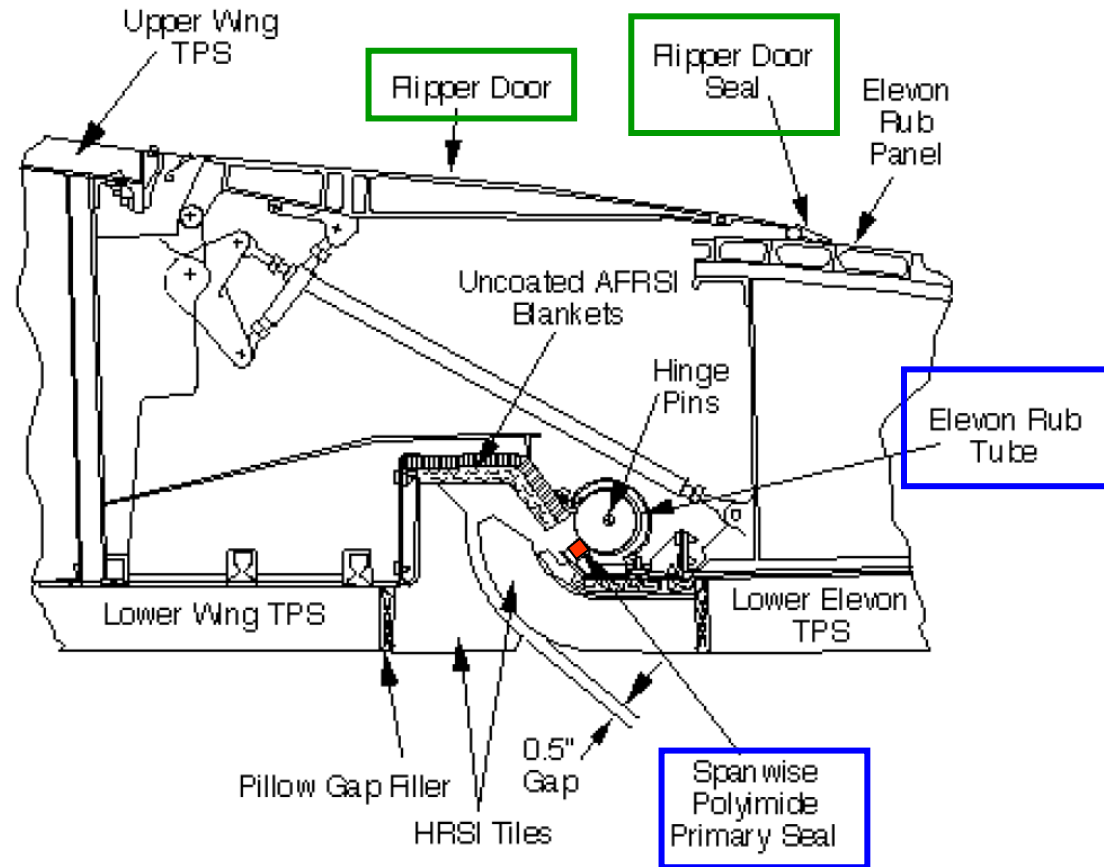
# Shuttle Elevon Cove Seal Area

Lower wing area: tile lined, tortuous path ending in a spanwise wiper seal. (precision fit wiper)

- Materials:
  - Wiper seal: polyimide seal which contacts the elevon rub tube.
  - Elevon rub tube: 2024-T3 Aluminum

Upper wing area: actuated metallic flipper door. Flipper doors hinged on the wing trailing edge and move in concert with the elevon to ensure a proper seal.

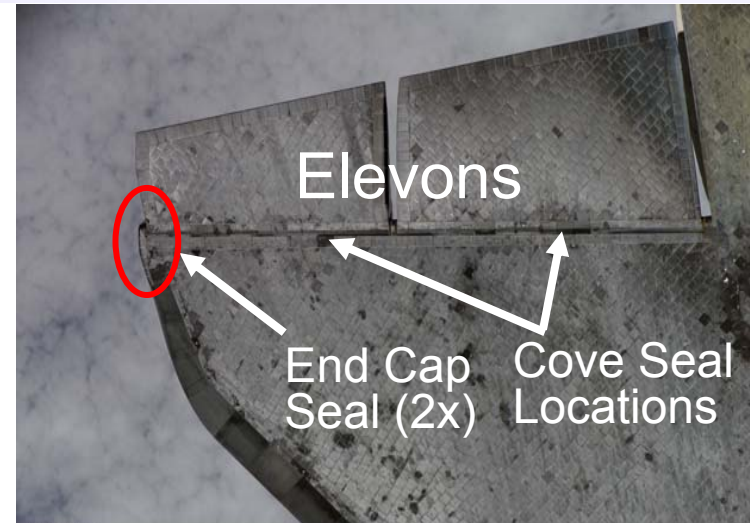
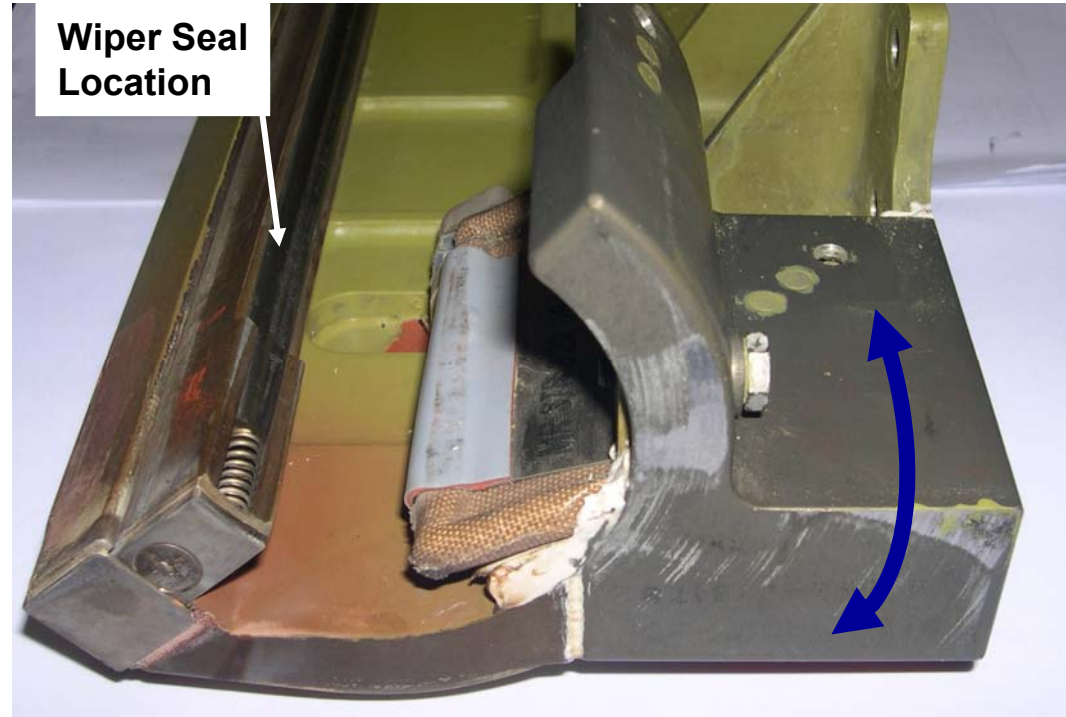
- Materials:
  - Inconel
  - Exposed metallic surface is coated with white paint to optimize the thermal emissivity



# Shuttle Elevon Cove Seal Area (Cont'd)

## End Cap Seals:

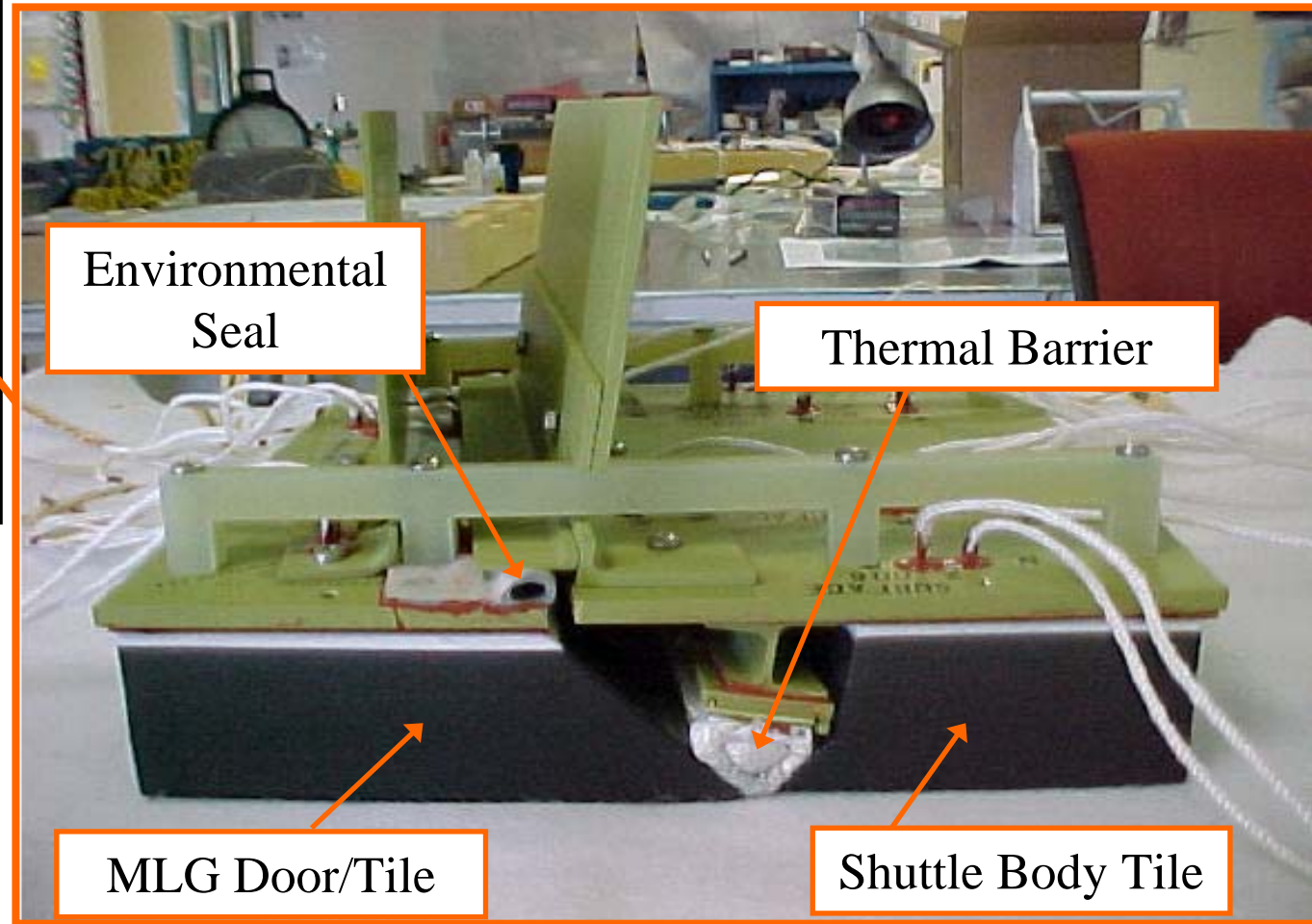
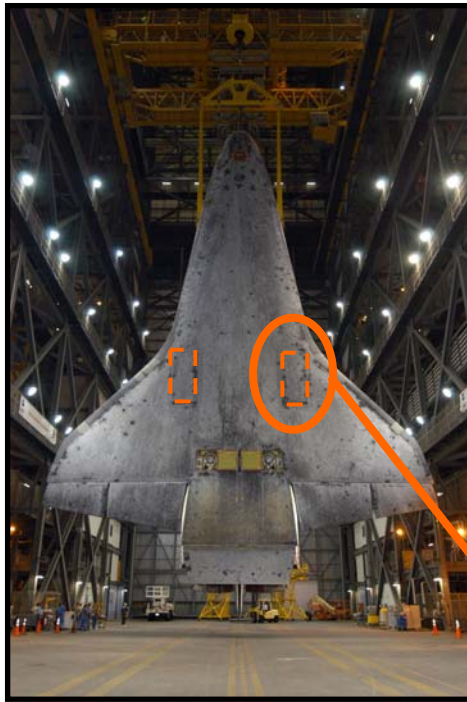
- Inboard/outboard ends of seal: spring loaded seal allows for inboard and outboard floating of elevon due to thermal expansion mismatches between the wing and elevon.
- Materials:
  - Columbium Alloy: C-103
  - Coating: R512E (Cr,Fe,Si)
  - Operating Temp: 2000F (rated for 2400F)



Ref: C. Snapp, Report KLO-00-006, October 17, 2000

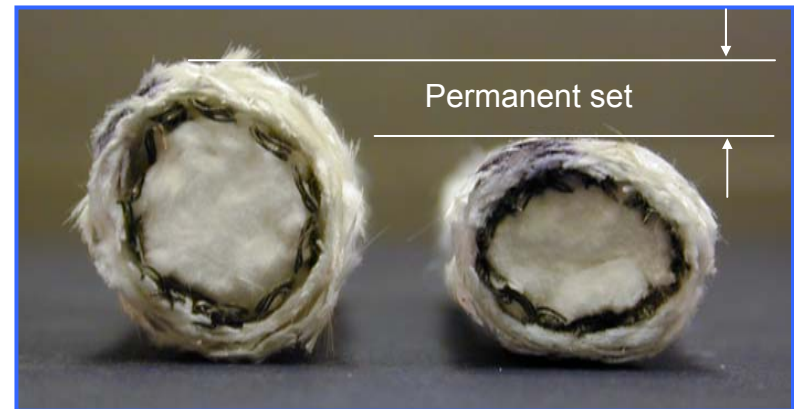
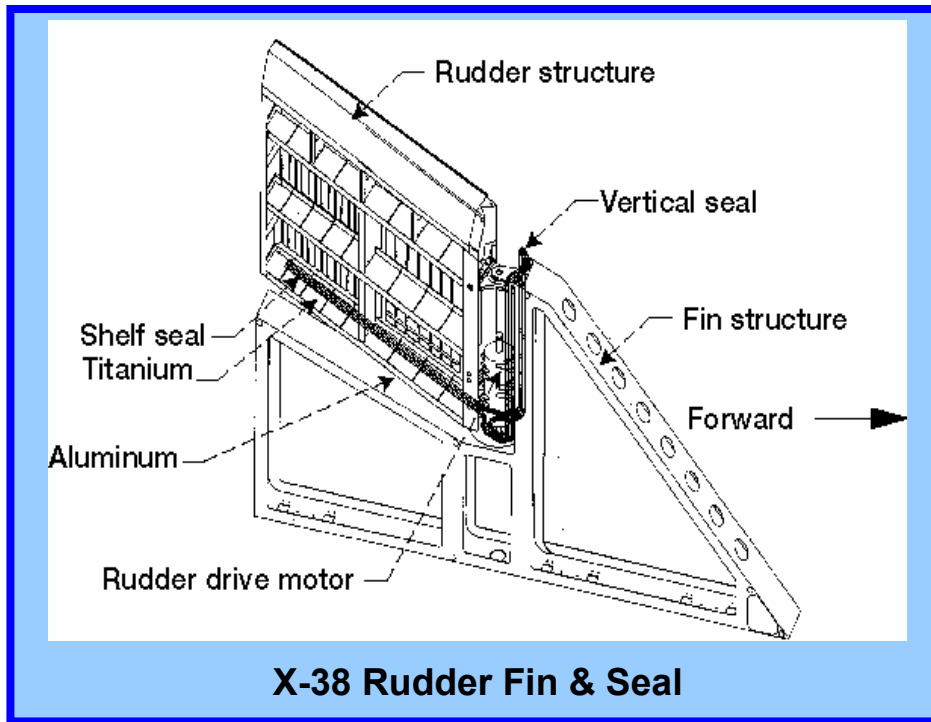


# Main Landing Gear (MLG) Door and Seals



# Performance Criteria for High Temperature Seals

- Good insulating properties → block heat flow
- Minimize leakage
- Help maintain smooth outer mold line minimizing steps and gaps
- Good flexibility → conform to complex airframe system geometries
- Good resiliency → maintain contact with opposing surfaces under dynamic conditions and over many cycles – minimize permanent set
- Good wear resistance → maintain seal integrity under dynamic conditions and over many cycles



# Establishing Vehicle Seal Design Requirements

- Leakage limits -- Generally thermally driven with the following considerations:
  - Control surfaces:
    - Prevent aerodynamic loss/drag and
    - Prevent overheating of hinge and drive mechanisms
  - Landing gear doors:
    - Prevent overheating of wheels and gear system
    - Smooth outer mold line (OML) → step/gap tolerance set by program
- Temperature, Pressure
  - Work with aerodynamic and thermal/structures communities to establish
  - Varies with vehicle trajectory, dynamic pressure, angle of attack, etc.
- Gap change:
  - Caused by differential expansion rates of adjoining structures
  - Work with thermal/structures community to establish.
- Life: Driven by system level requirements
  - Control surfaces: anticipated stroke both large and “dithering” per mission → multiplied by number of missions.
  - Doors: number of openings/closings both during mission and during pre-flight check-out → multiplied by number of missions.
- Design requirements-- A personal note:
  - Often requires determination by seals engineer to enumerate early enough that appropriate development can be done in-time.
  - Requirements change during development cycle: constant communication required.

# Challenges for Advanced Airframe Thermal Barriers (T/B)



VS.



- ◆ **Large depth of section for TPS (Shuttle tiles)**

- Internal seals are further from OML
- More room for redundant TB's

- ◆ **TPS tiles are excellent insulators → limit heat transfer**

Lower temperatures  
More margin

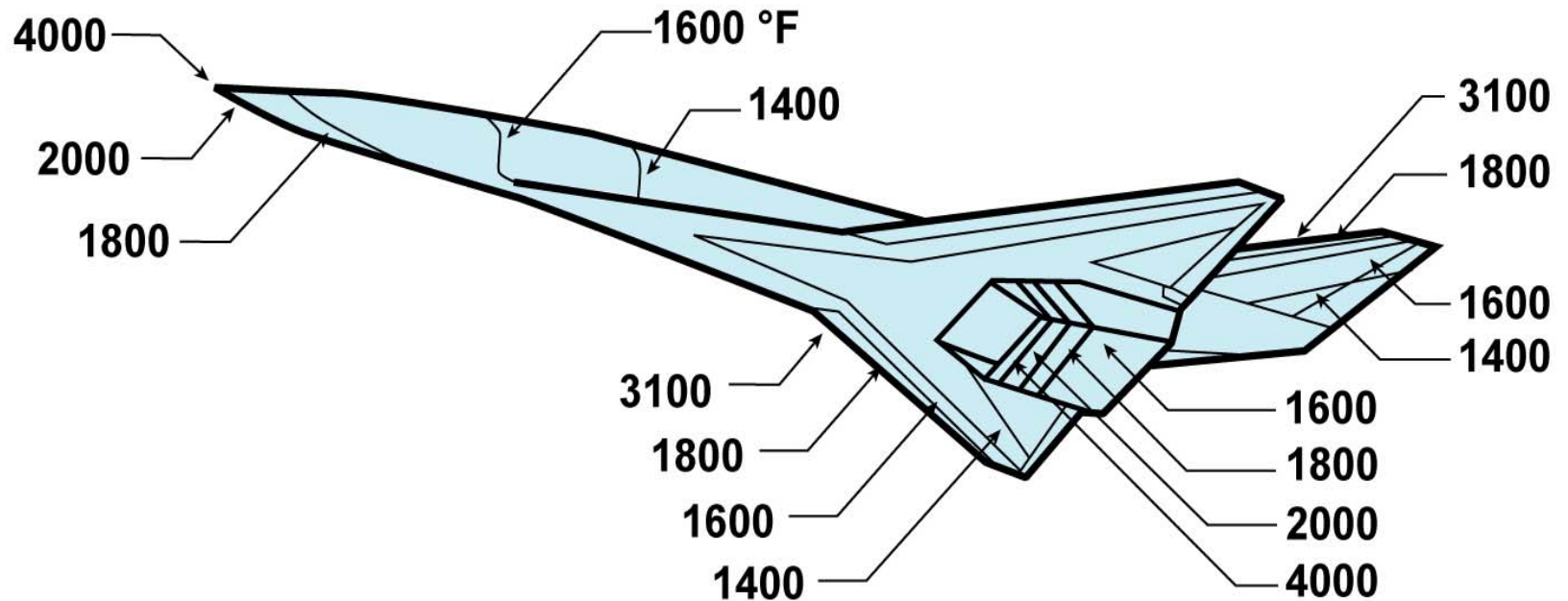
- ◆ **Smaller depth of section for ceramic-matrix-composite TPS panels.**

- Internal seals closer to OML
- Less room for redundant TB's

- ◆ **CMC panels have high heat conductivity → more heat transferred to seals**

Higher temperatures  
Less margin

# Predicted Equilibrium Surface Temperatures for Hypersonic Cruise at Mach 8, 88 kft.



# **NASA Test Capabilities to Evaluate Advanced Seal Concepts**

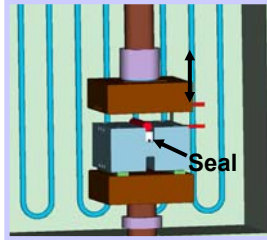


# GRC Control Surface Seal Evaluation Roadmap

## Hot Compression Testing:

Resiliency retention vs.

- Temperature
- Compression level
- Load cycling
- Long-term static load



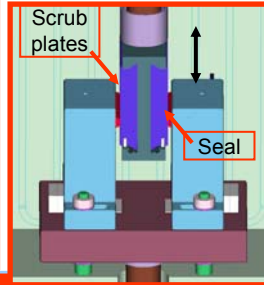
✓ Rig Development

Testing

## Hot Scrub Testing:

Wear rates & frictional loads vs.

- Temperature
- Compression level
- Stroke rate & number of cycles
- Rub surface conditions (material, surface roughness)
- Scrub direction (e.g., transverse vs. wiping)



✓ Rig Development

Testing

## Thermal-Acoustic Testing:

- Seal structural integrity in high acoustic/ thermal environment

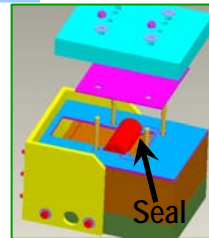
Rig Development

Testing

## Seal Flow Testing:

Measure Flow vs:

- Delta Pressure
- Compression level; Gap size
- Pre- and Post- Scrub or compression
- Rub surface conditions (material, surface roughness)

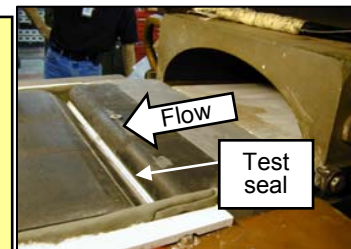


✓ Rig Development

Testing

## Arc Jet Tests:

- Thermal endurance in relevant environment
- Abrasion effects due to movement of control surface
- Compression level & gap size effects
- Database to anchor aero-thermal analyses



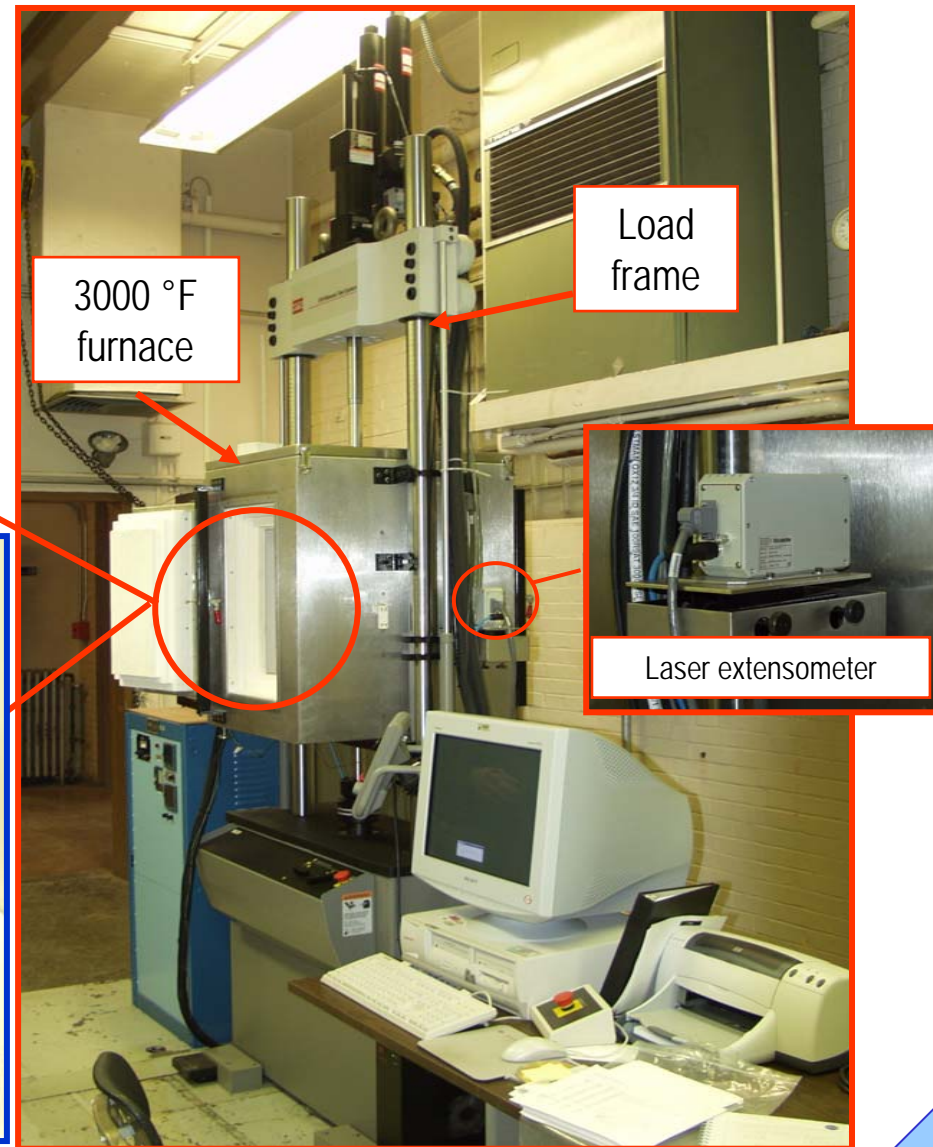
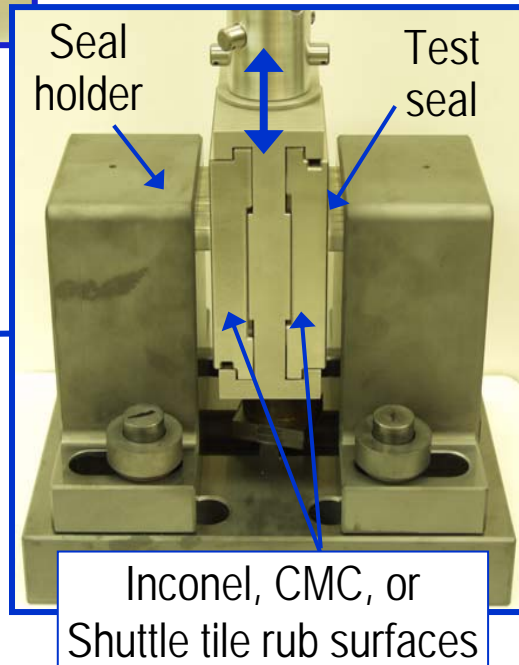
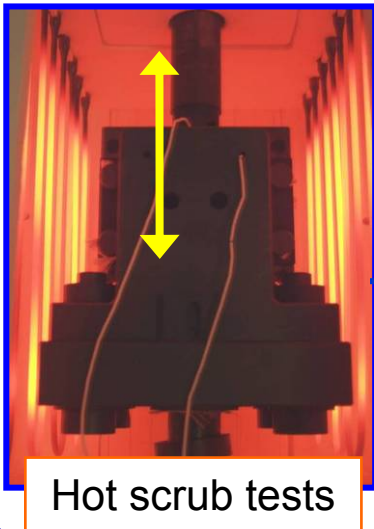
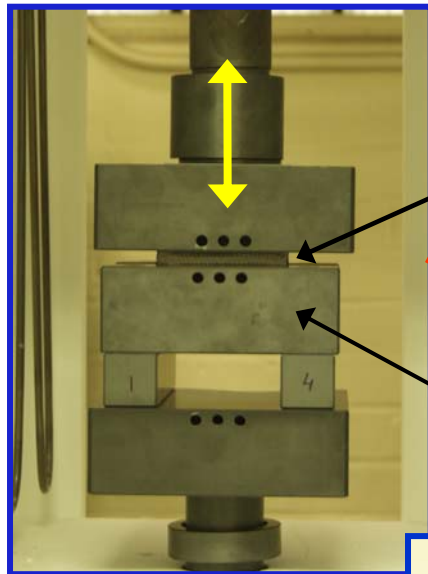
✓ Rig Development

Testing

TRL: Technology Readiness Level

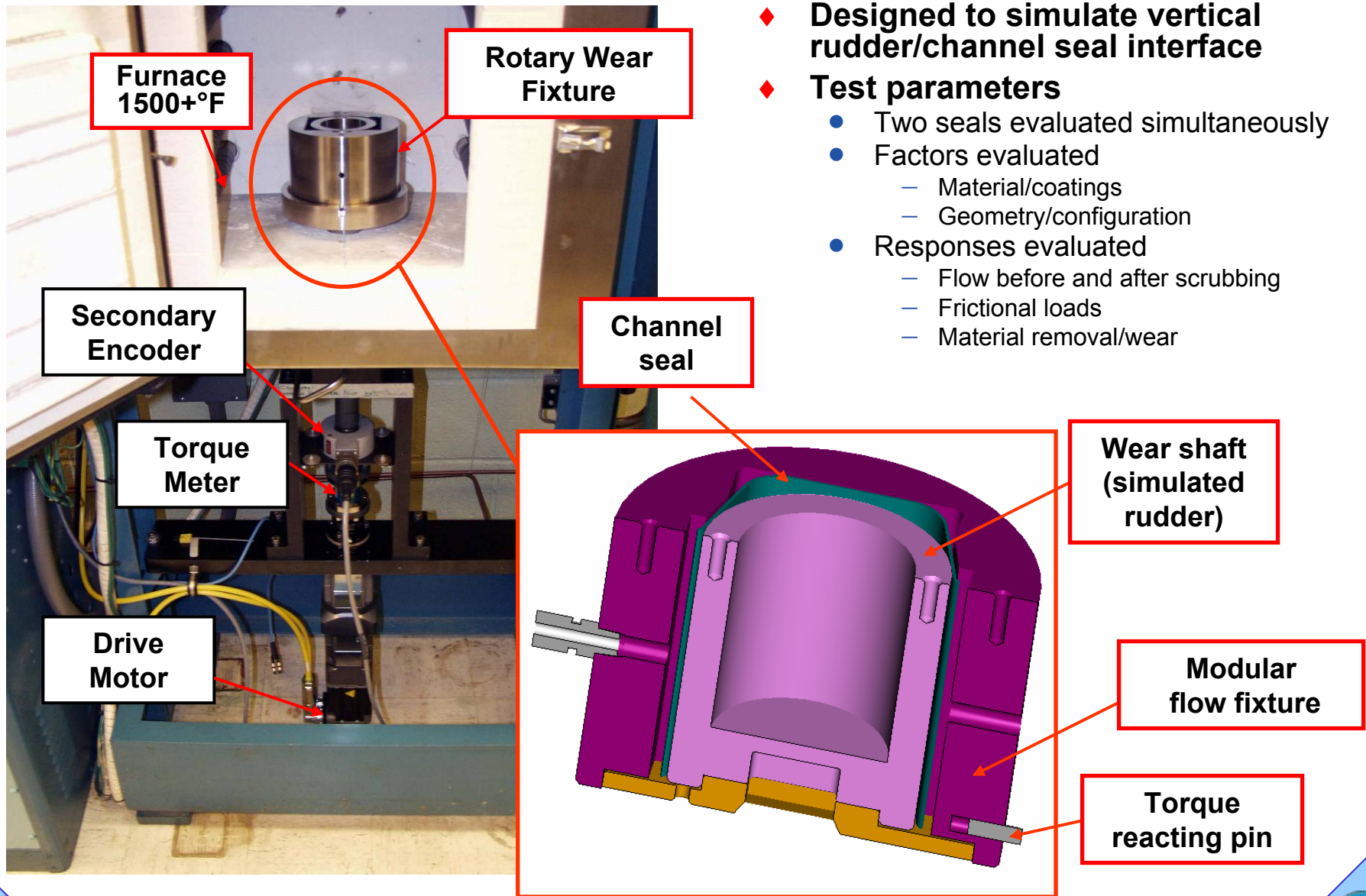
Development timeline / Increasing TRL

# GRC Hot Compression/Scrub Seal Test Rig: Overview



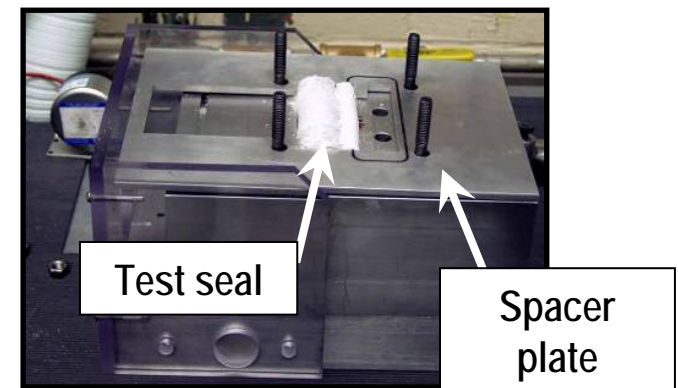
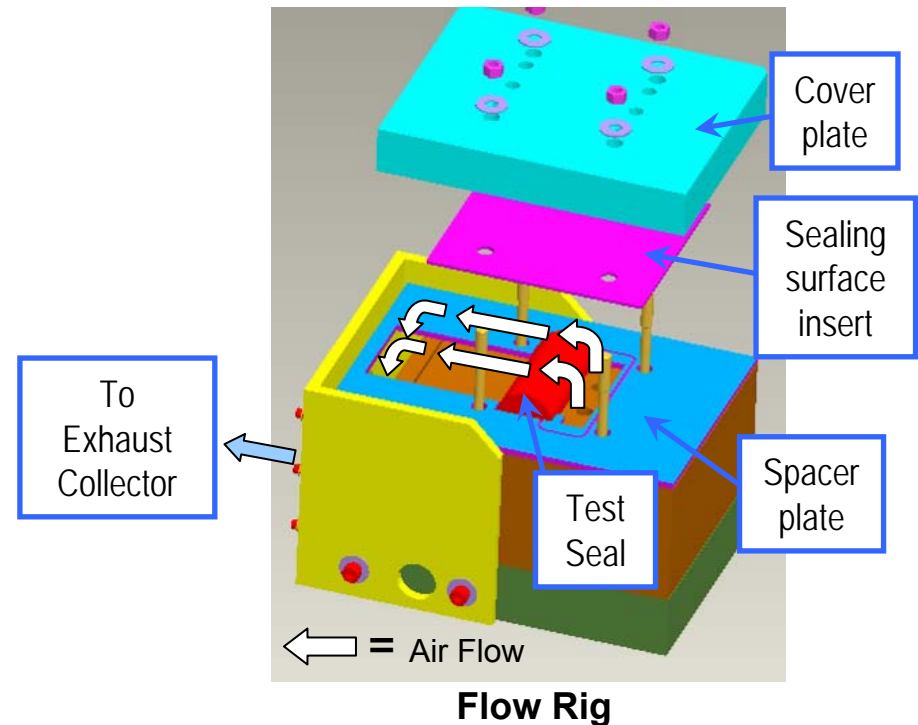


# New GRC High Temperature Rotary Wear Rig



# Linear Flow Fixture – RT Flow Tests

- Test Type: Room temperature flow tests
- Purpose:
  - Assess flow blocking capability of seals against realistic sealing/scrub surfaces (data can be used for thermal models)
- Seal Types:
  - Thermal barriers, gap fillers, wafer seals, elastomeric seals, etc.
- Capabilities:
  - Gas: Air
  - Pressure range: 0 – 100 psig max
  - Flow range: 0 – 3000 SLPM max
  - Gap range: Set via spacer plate
  - Seal compression range: Variable
  - Sealing/scrub surface:
    - Metallic, CMC, ablator, etc.
    - Various surface roughness



# Seal Arc Jet Test Fixture Development

## ♦ Objective:

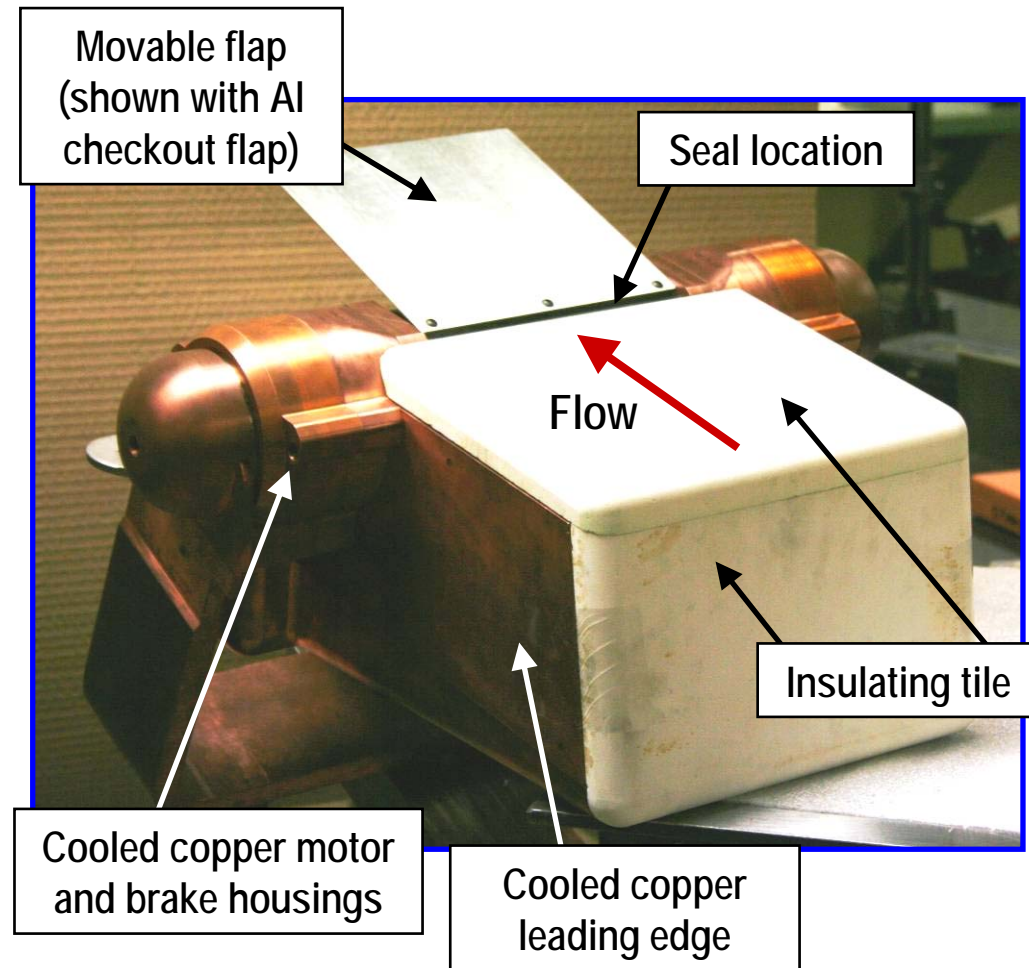
- Test seals and control surfaces under simulated heating conditions in JSC arc jet

## ♦ Features:

- Unique GRC design permits testing of different seal and flap designs
- Motor-driven flap (C/SiC, MR&D/GE) moves during testing to simulate flight
- Adjustable angle-of-attack and yaw angle permit testing of different flow conditions

## ♦ Status/Schedule:

- Fabrication complete
- Assembly complete
- Testing TBD (currently unfunded)



Seal arc jet test fixture assembly

# **Seal Performance Assessments**

# Case Study #1

## Space Shuttle Main Landing Gear (MLG) Door Environmental Seal

**Main  
Landing  
Gear  
Door**

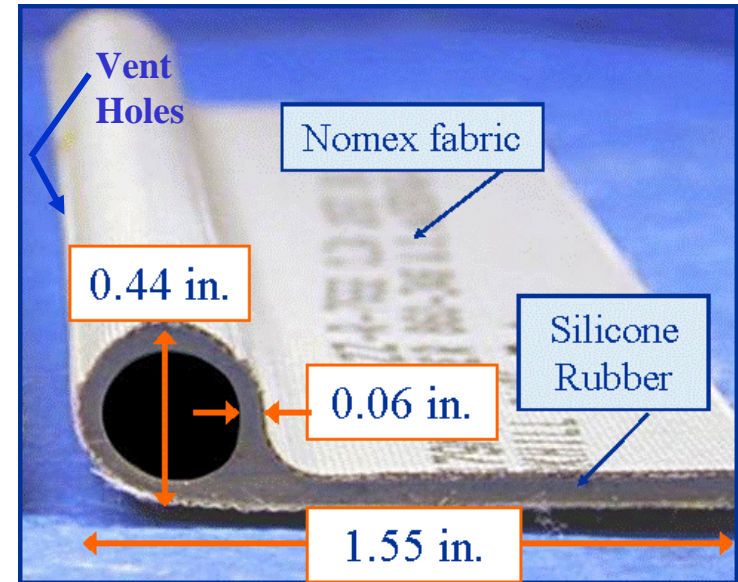
**Seal**





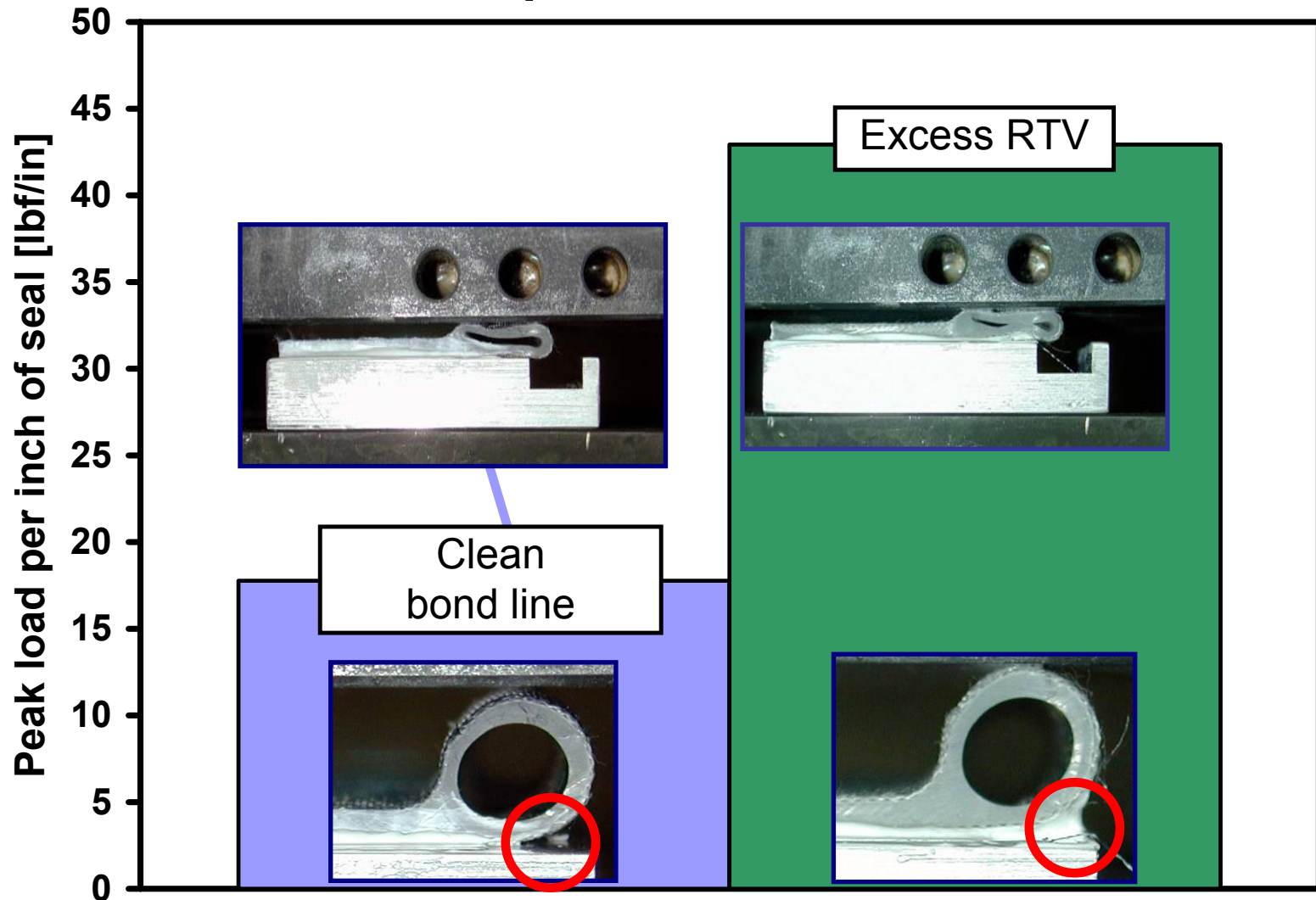
# Background on MLG Door Seal Issue

- ◆ **Columbia Accident Investigation Board (CAIB) requested investigation of Main Landing Gear (MLG) door environmental seals**
  - Assess potential contribution of seals to loss of Columbia
  - Assess safety issues of seals for future flights
- ◆ **Installation of new environmental seals on Discovery prevented full closure of MLG doors**
  - Door closure mechanism near-overload
  - Previous experience (ca. 1991) demonstrated that overload conditions damaged door closure mechanism
- ◆ **NASA Johnson Space Center (JSC) requested testing of MLG Environmental Seals at NASA Glenn Research Center (GRC)**
  - Room temperature compression tests
  - Flow tests



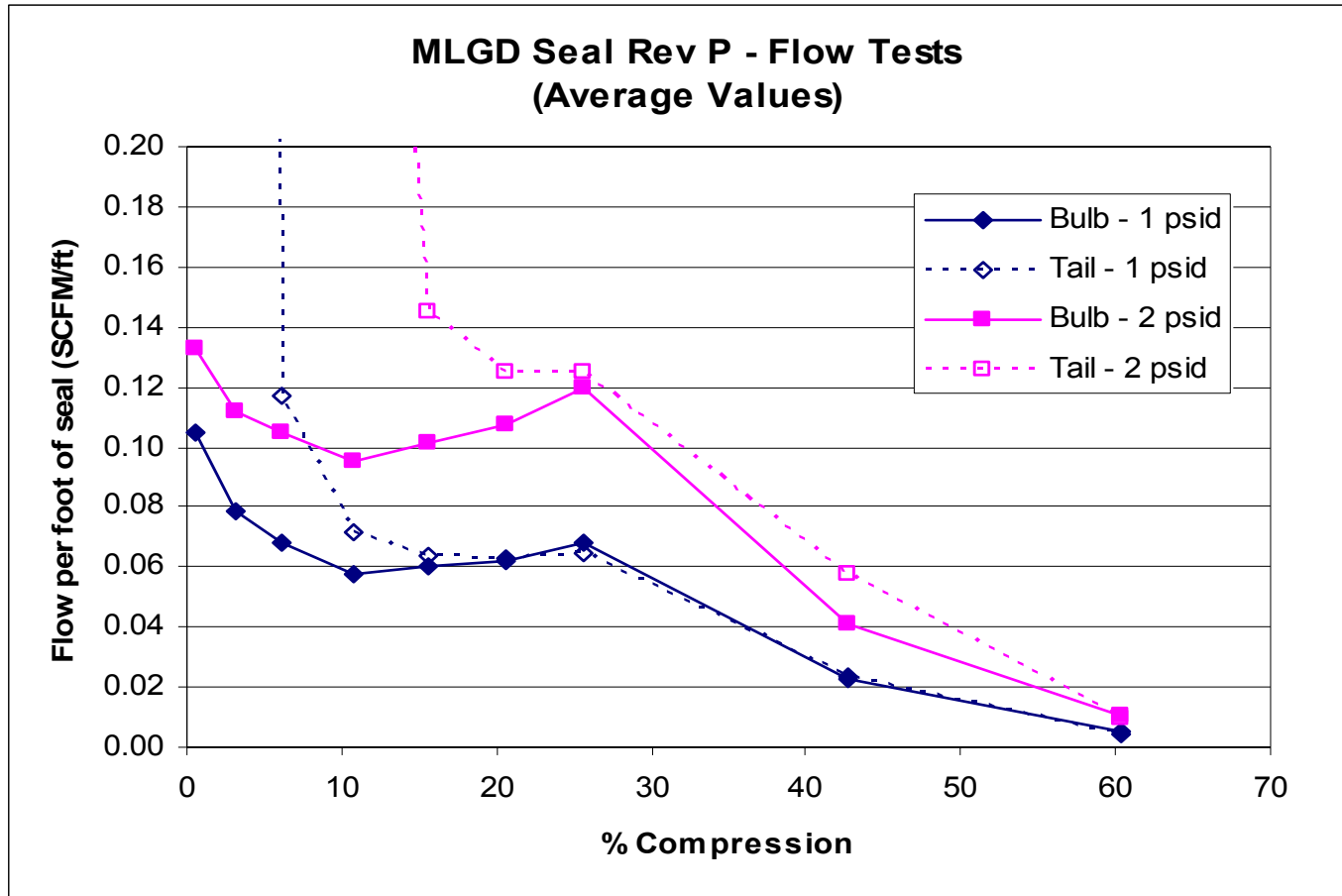
**Environmental "P"- seal**

# MLG Compression Test Results



- Excess RTV increased peak load by ~2.5x
- Removal of RTV allowed Discovery doors to close
  - Modified RTV application approach, custom shims

# MLG Flow Test Results (Rev P)



- At lower compression levels (<20-30%), leakage was significantly higher when seal was pressurized from tail side (i.e. vent holes not exposed to  $\Delta P$ )
  - Vent holes allow hollow-bulb pressure venting during ascent
- When pressurized from bulb side, inflation of bulb occurred via vent holes due to  $\Delta P$  and resulted in reduced leakage
- As compression increased, effect of inflation began to diminish and results for pressurization from tail and bulb sides converged



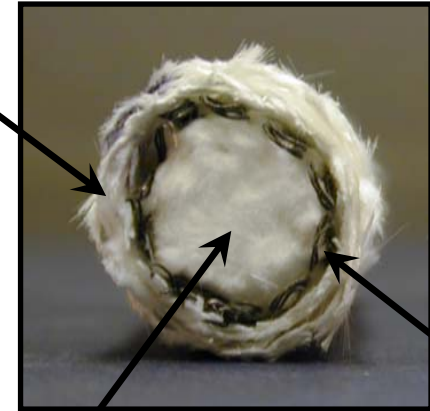
**Case Study #2**  
**Thermal Barrier Seal Assessments:**  
**Shuttle/X-38 Baseline Design**

# Spring Tube Thermal Barriers: Attributes

- Baseline design (Shuttle, X-38 heritage):
  - Inconel X-750 spring tube
  - Saffil core
  - 2-layer Nextel 312 ceramic fabric sheath
- Attributes:
  - Flexibility through braided structure, conforms well to unusually-shaped structures
  - Modest leakage rates
  - Potential for high temperature service using superalloy spring tube
  - Low unit loads preventing tile damage

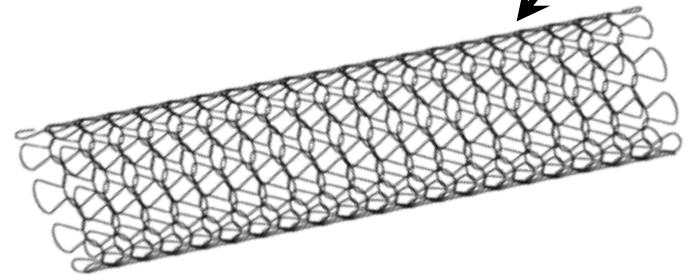
Note: see Appendix A for Thermal Barrier initial sizing as function of initial gap and gap size change

**Nextel  
braided  
Sheath**



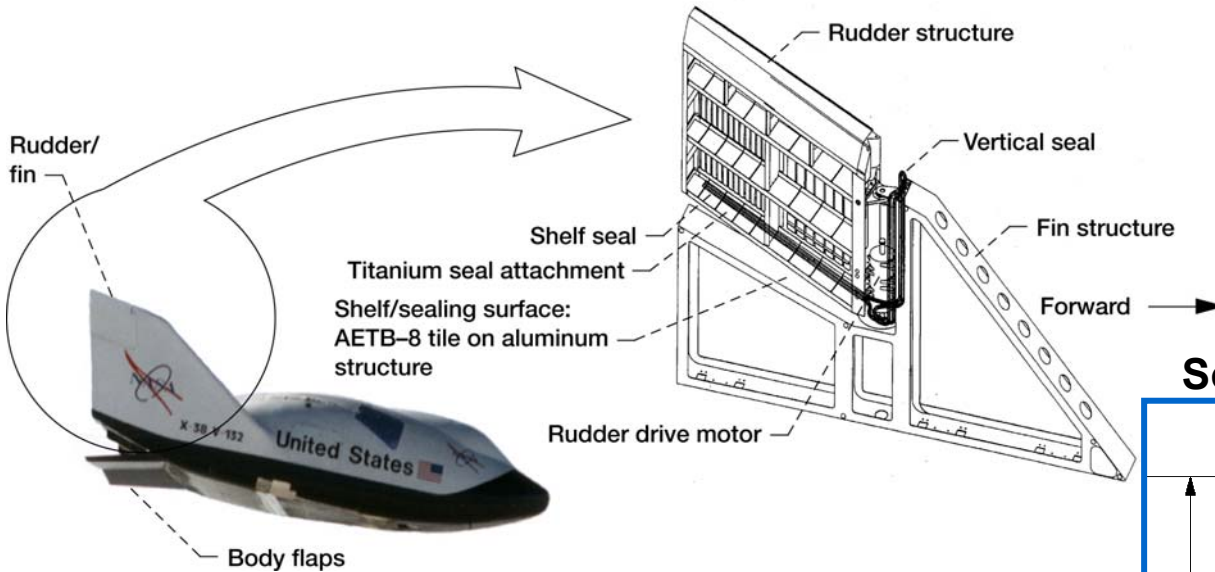
**Saffil  
core**

**Spring  
tube**

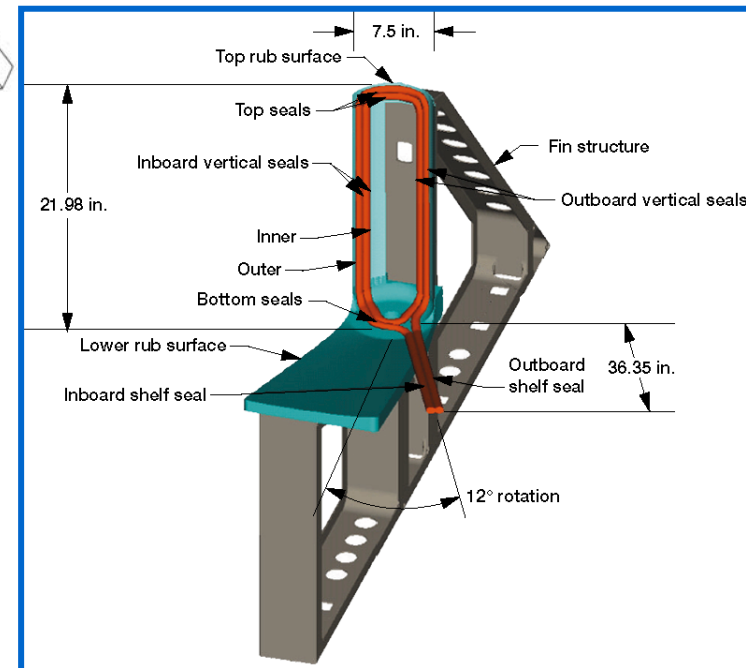


# X-38 Rudder/Fin Seal Assembly

## Rudder/Fin Seal Locations



## Solid Model of Rudder/Fin Seal

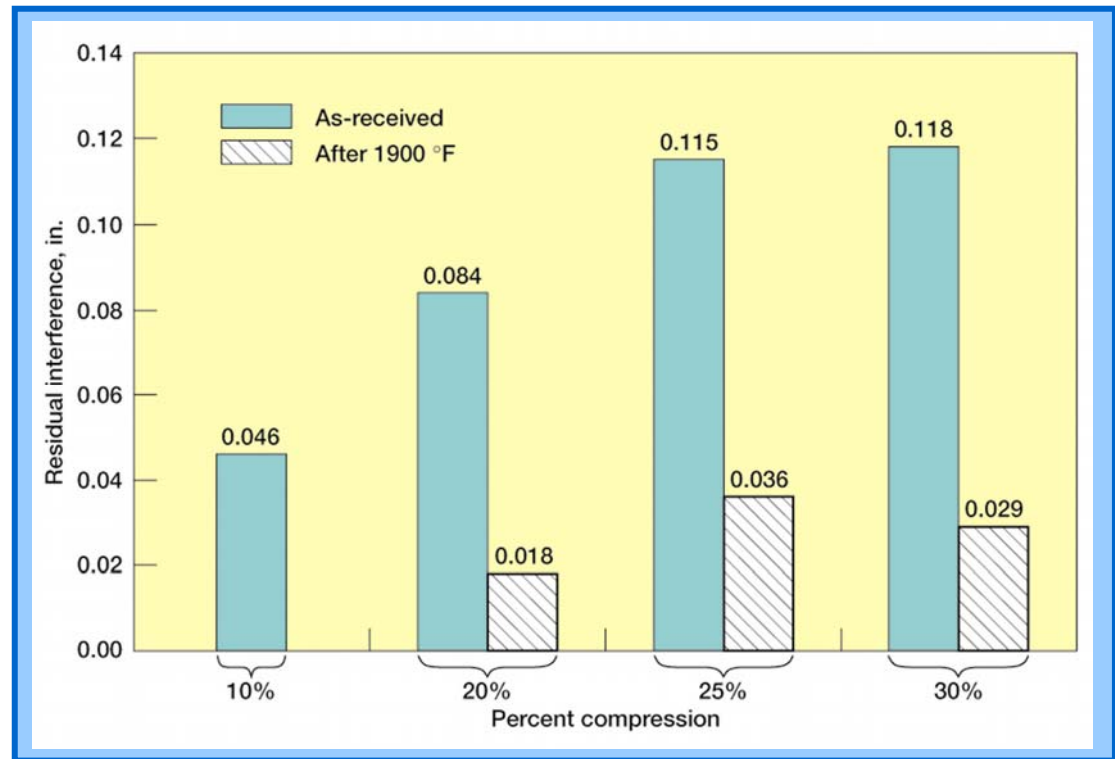


## Thermal Barrier Design:

- Redundant inboard/outboard thermal barriers
- Goal: Prevent heat from reaching actuator
- Nominal 20% compression; 0.25-in. gap

# Baseline Design: Compression Test Results-Resiliency

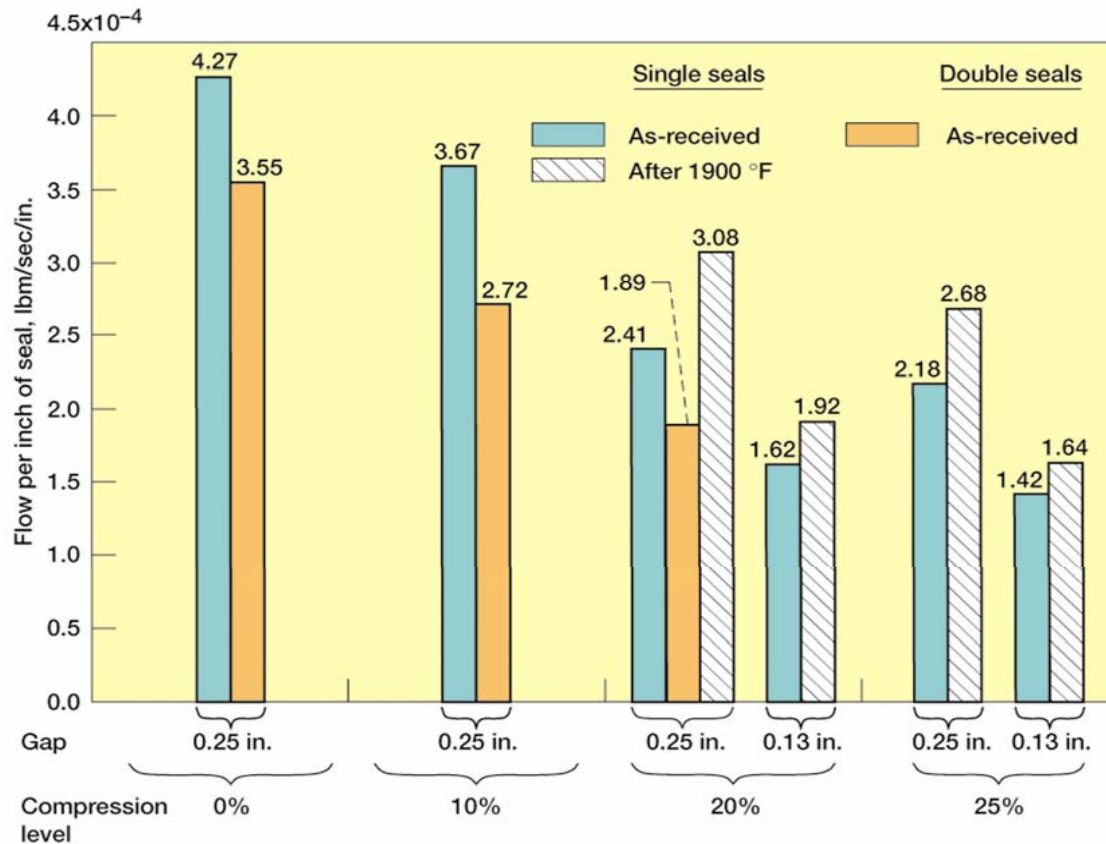
- Resiliency/springback for as-received seals increased with percent compression
- Large loss of resiliency for temperature-exposed seals
  - Expected cause: Permanent set of Inconel X-750 spring tube
  - Large loss of resiliency a concern for future highly-reusable vehicles with long life requirements



**Loss of resiliency required X-38 designers to stiffen surrounding structures to prevent loss of sealing contact during re-entry.**

# Baseline Design: Flow Test Results

**Delta P = 56 psf**  
**(peak pressure during X-38 re-entry)**



- Flow rates decreased with increase in compression levels and decrease in gap size.
- Addition of second seal into flow path reduced flow rates by 17 to 26% compared to single seals
- Single seal flow after 1900°F exposure increased up to 28% compared to as-received seal due to permanent set.

# Control Surface Seal Arc Jet Tests

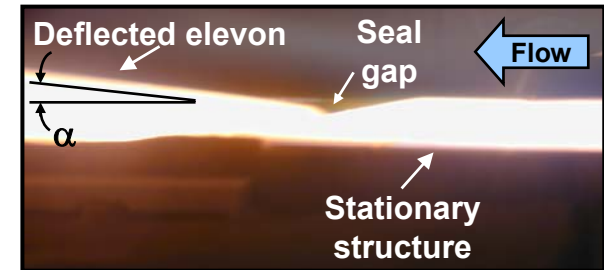
## Baseline Thermal Barrier Design

### Objective:

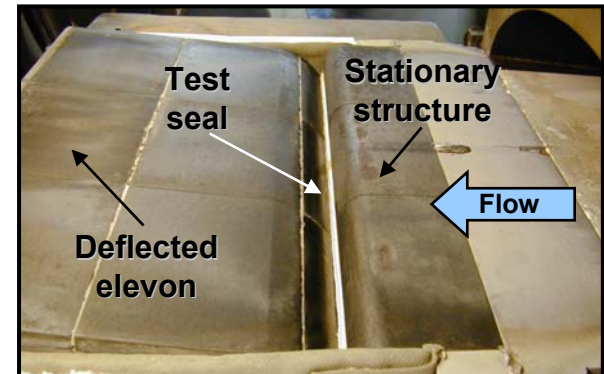
- Evaluate candidate control surface seals under relevant thermal conditions in NASA Ames arc jet facility
- Determine temperature drop across seal at various control surface angles

### Test Seal:

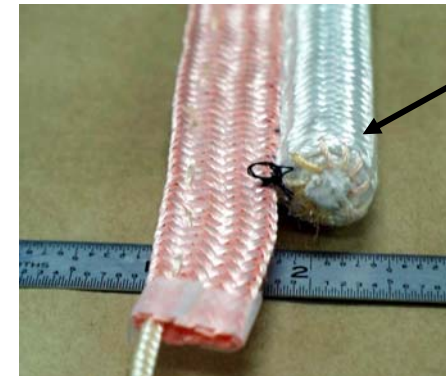
- Single X-38 rudder/fin seal with 9 pcf Saffil core; Inconel X-750 spring tube, Nextel 312 overbraid
- 20% compression



Side view of test article during arc jet test



Arc jet test article with seal installed

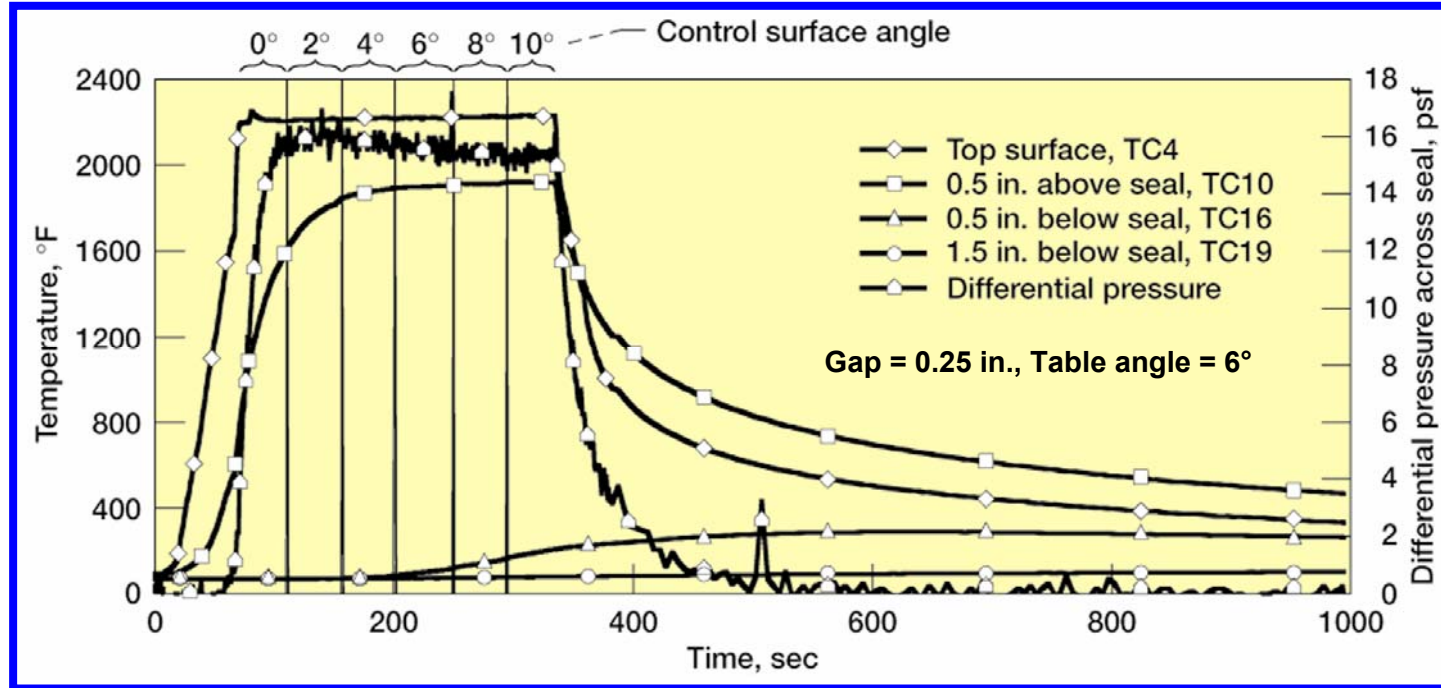


Thermal barrier w/  
stitched-on  
tail



# Arc Jet Test Results-Seal Installed Baseline Design

- **Peak temperatures:**
  - 0.5 in. above seal = 1920 °F
  - 0.5 in. below seal = 210 °F
  - Temperature drop across seal location = 1710 °F (compared to 140 °F for open gap test)



- Average pressure differential across seal was 15.6 psf, 44% of predicted pressure drop (35 psf) during X-38 maximum heating

Installation of single seal caused large temperature and pressure drop across seal location as compared to open gap (separate test)

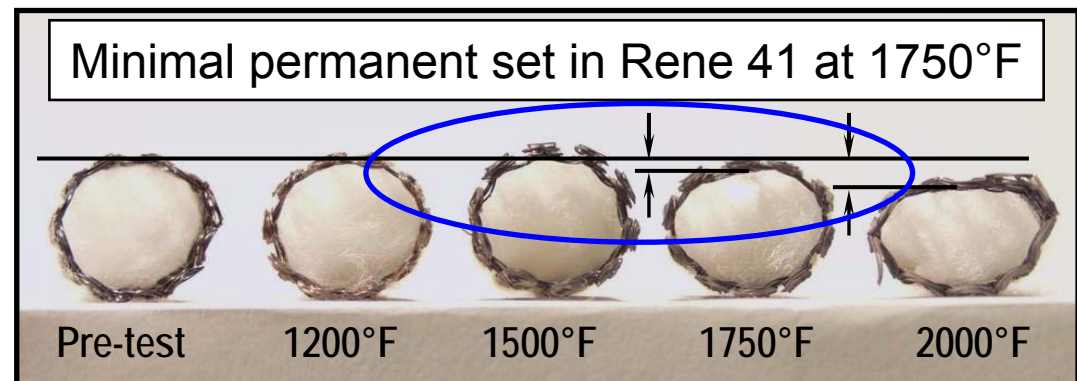
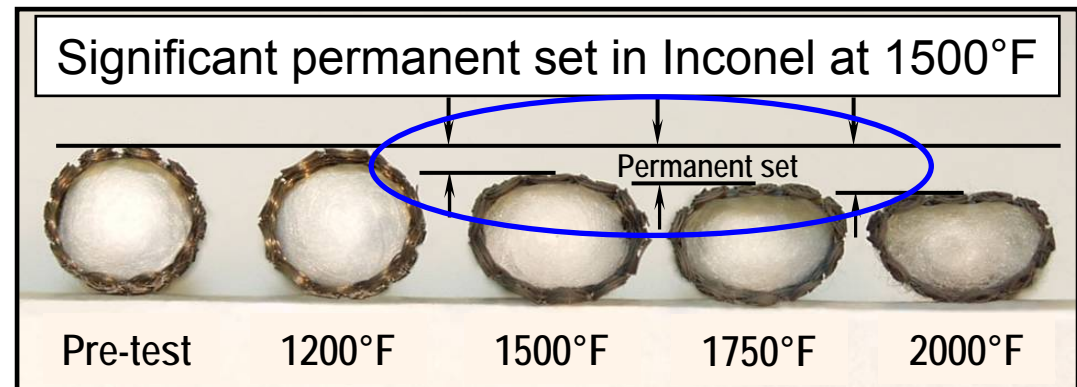
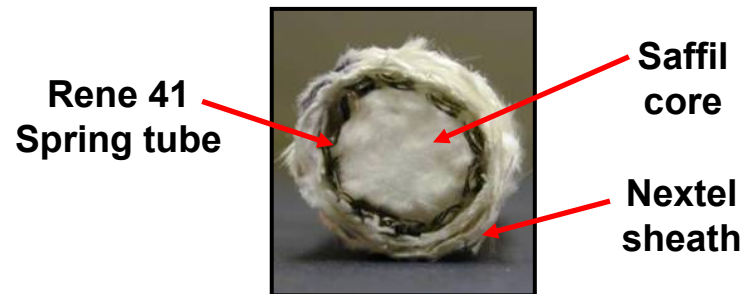
# **Thermal Barrier Seal Assessments: GRC Improved Design**



# GRC Improved Design: Spring Tube Seal Development

- Objective: Improve resiliency of spring tube seals at high temperatures
- Approach: Substitute higher strength Rene 41 for Inconel X-750 in knitted spring tube
- Positive outcome: Increased max use temperature to ~1750°F

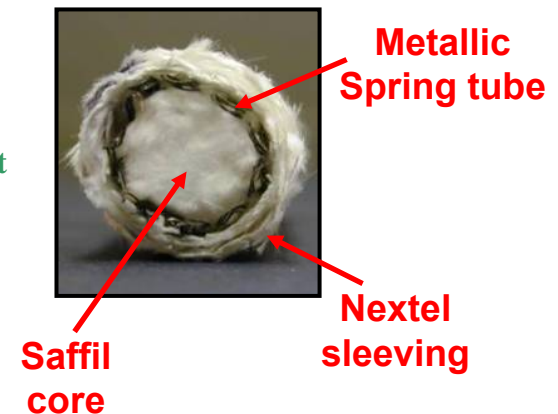
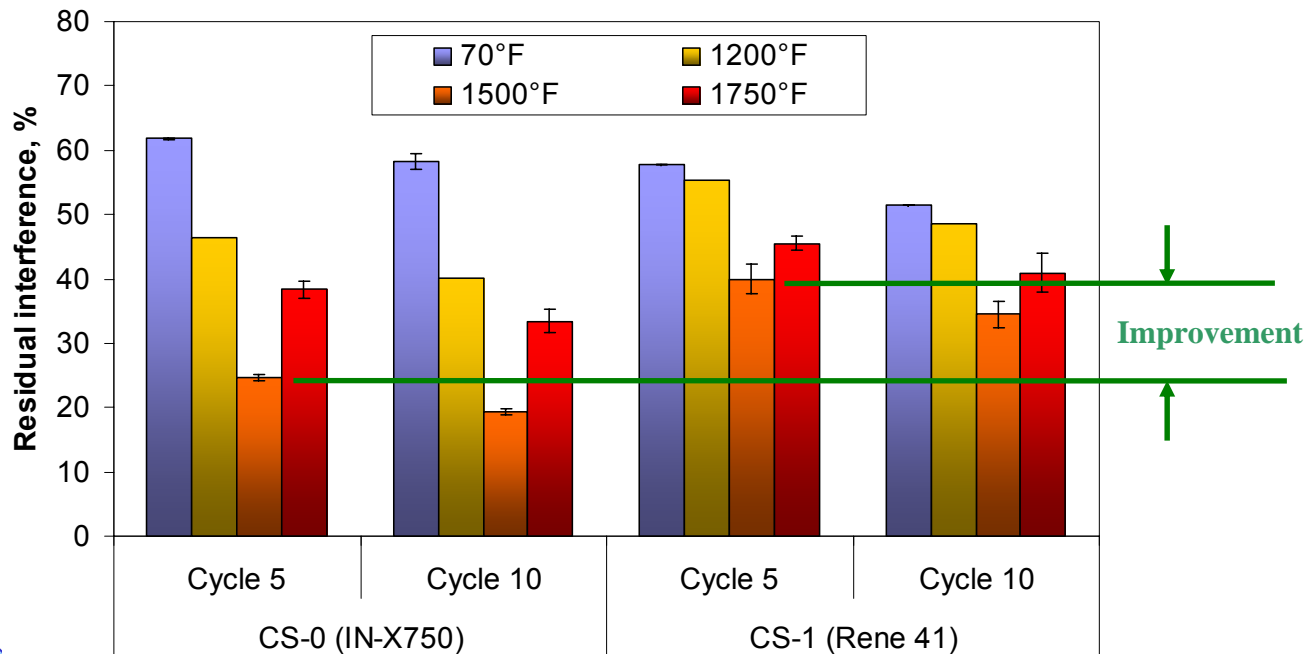
Note: GRC currently examining Nextel 440 (higher temperature, higher strength fiber) to replace Nextel 312 sheath



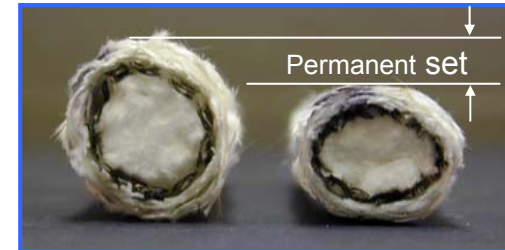
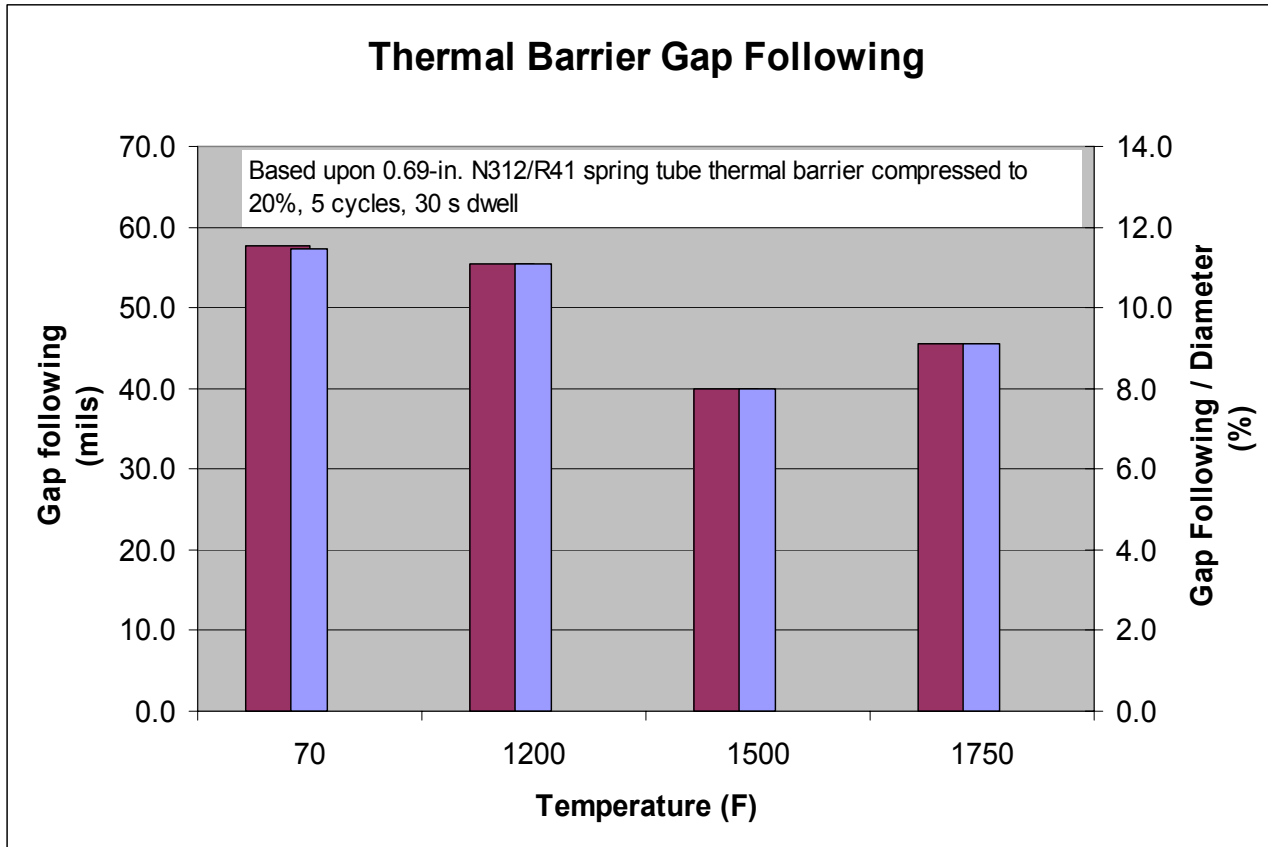
**Note:** Tests above performed on spring tubes alone  
(Cotton fill shown for clarity)

# GRC Improved Design: Resiliency Improvement

- ♦ **Seal with Rene 41 spring tube showed slightly higher resiliency at elevated temperatures (20% on average) vs. sample with IN X-750 spring tube**
  - Performance enhancement not as great as with spring tube alone
  - Other components may contribute more than previously thought
- ♦ **At the tested gap, flow values were comparable for both thermal barriers designs**
  - If gap were to increase, sample with Rene 41 spring tube would likely exhibit less leakage than sample with Inconel X-750 spring tube



# GRC Improved Design: Gap Following vs. Temperature



## Thermal Barrier

- 0.69" Dia.
- Materials:
  - Sheath: Nextel 312
  - Spring Tube: Rene 41
  - Core: Saffil

- Thermal barrier gap following capability generally declines with increasing temperature.
- Greater gap following obtained by either:
  - Increasing seal barrier size
  - Finding higher temperature spring alternatives: current research topic at NASA Glenn

# Summary: Vehicle Seals

- Hypersonic vehicles pose demanding challenges for seal designers including both temperature and time-at-temperature:
  - Control surface seals: 1500-2200°F
  - Leading edges: 3000+°F
- Sustained hypersonic flight poses challenges to vehicle seals.
  - Re-entry vehicles experience high heating for ~15 minutes or less allowing radiation to dissipate heat (e.g. Shuttle)
  - Global reach vehicles traveling in the atmosphere for 2 hrs will need to sustain much higher temperatures
    - Less able to take advantage of bulk heat soak
    - Require high temperature seals and preloaders.
- Smaller depth of section for TPS (CMC panels) results in the following additional challenges:
  - Internal seals closer to OML
  - Less room for redundant thermal barrier's
  - CMC panels have high heat conductivity → more heat transferred to seals

# Summary: Vehicle Seals (cont'd)

- For most effective seal performance & lowest leakage
  - Thermal barrier and environmental seals are used synergistically to harvest the best features of both elements. (e.g. Shuttle Main and Nose landing gear doors)
- Design requirements often evolve significantly during life of program requiring seal engineer diligence.

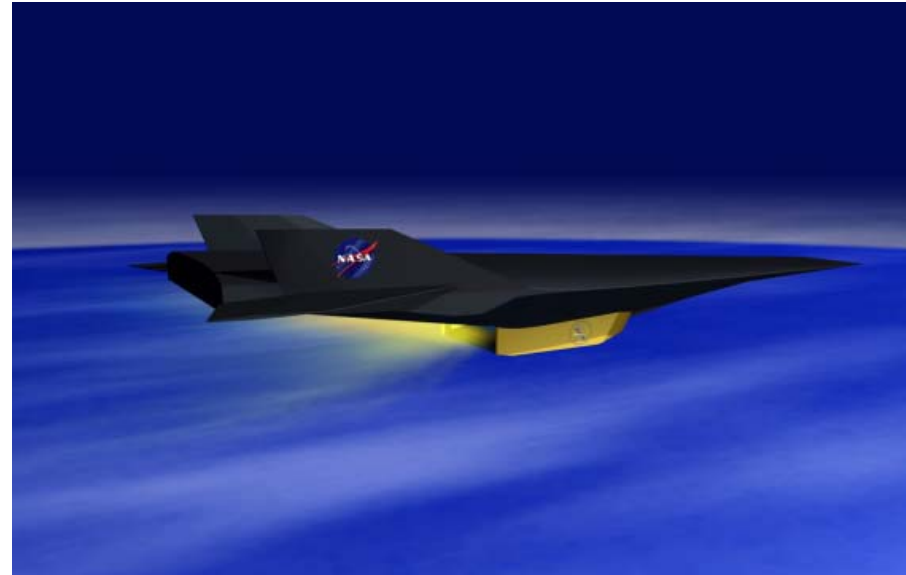
Example:

- Vehicle trajectory change → change in vehicle aero-heating
- → Increased structure and seal operating temperature
  - → May need different seal material
- → Increased structure temperatures may result in different gap changes
  - → May need different or more capable seal or preloader design.



# Future Work: Control Surface Seals

- **Sustained hypersonic flight requires**
  - Novel designs that can conform to structural deformations
  - High temperature seal materials for 2000+°F sustained (2+ hrs) operation
  - High temperature seal energizers to ensure proper preload against mating surface
    - GRC examining ceramic spring tubes
  - Seal Reusability
  - Demonstration tests of final configurations via methods discussed



## Section 9.4: Propulsion Seals



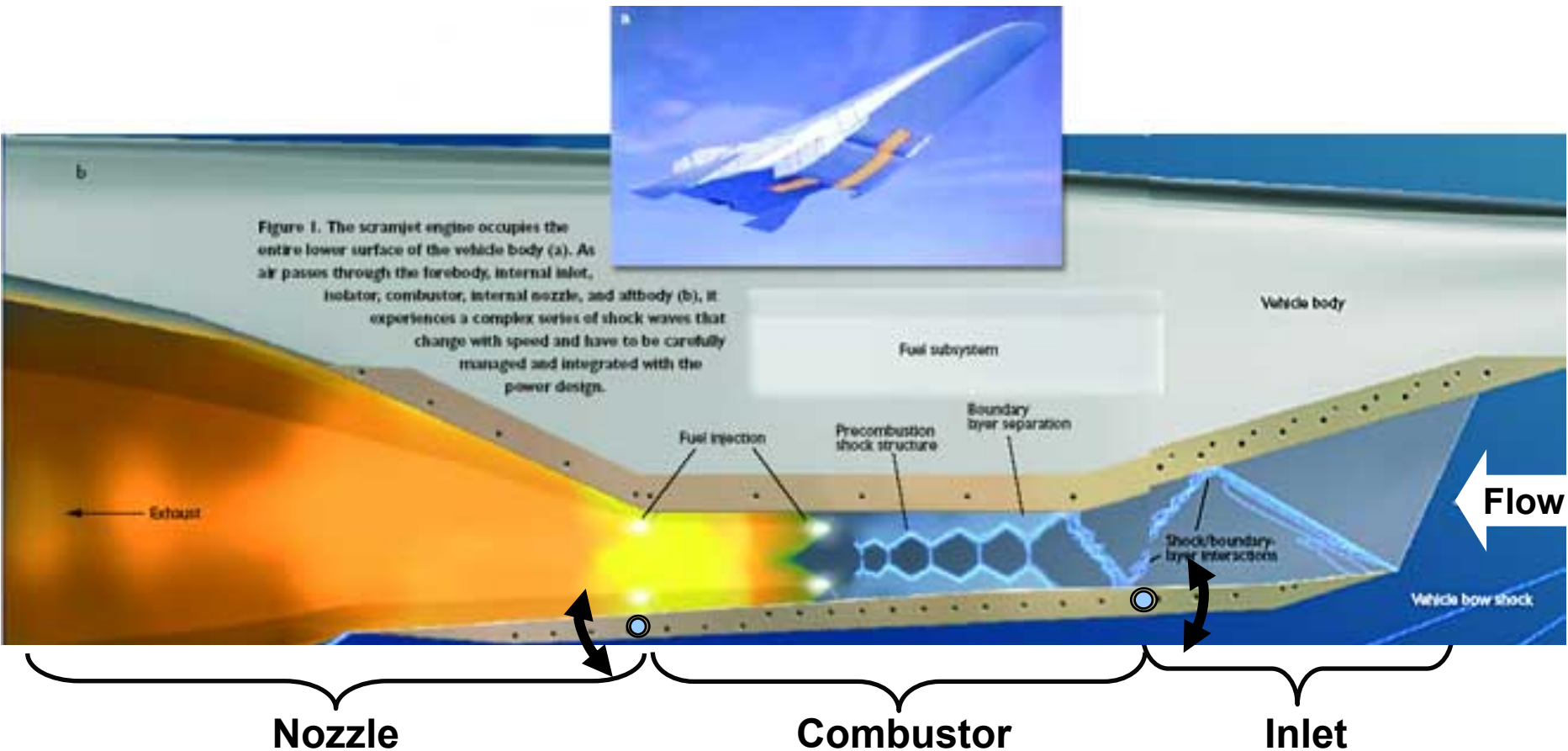
**Pratt & Whitney Rocketdyne's X-1 scramjet engine powers first X-51A simulated flight at NASA Langley Research Center test facility.**

Ref: PW Web site  
[http://www.pw.utc.com/StaticFiles/Pratt%20%20Whitney/News/Fact%20Sheets/Assets/Documents/pwr\\_Hypersonics.pdf](http://www.pw.utc.com/StaticFiles/Pratt%20%20Whitney/News/Fact%20Sheets/Assets/Documents/pwr_Hypersonics.pdf)

# Outline

- Anatomy of ram/scramjet engine
- Seal design requirements
  - Establishing propulsion seal design requirements
- Seal concepts
  - Heritage 2-D nozzle seals
  - Braided rope seals
  - Wafer seals
- Thermal Analysis
  - National Aerospace Plane (NASP) Inlet/Combustor Seals
  - Hypersonic gap flow analyses
- Test capabilities to evaluate advanced seal concepts
- Seal performance assessments
  - Case Study 1: Braided rope seals
  - Case Study 2: Wafer seals
- High temperature seal preloader development
- Summary
- Future work
- References (end of package)

# Anatomy of Ram/Scramjet Engine



- For optimum thrust, moveable panels are required throughout engine
- Seals required to prevent damage to actuation system and parasitic losses

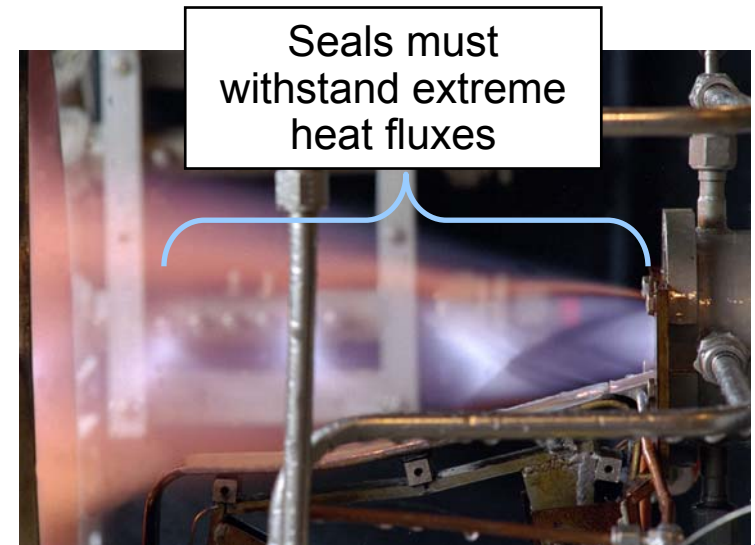
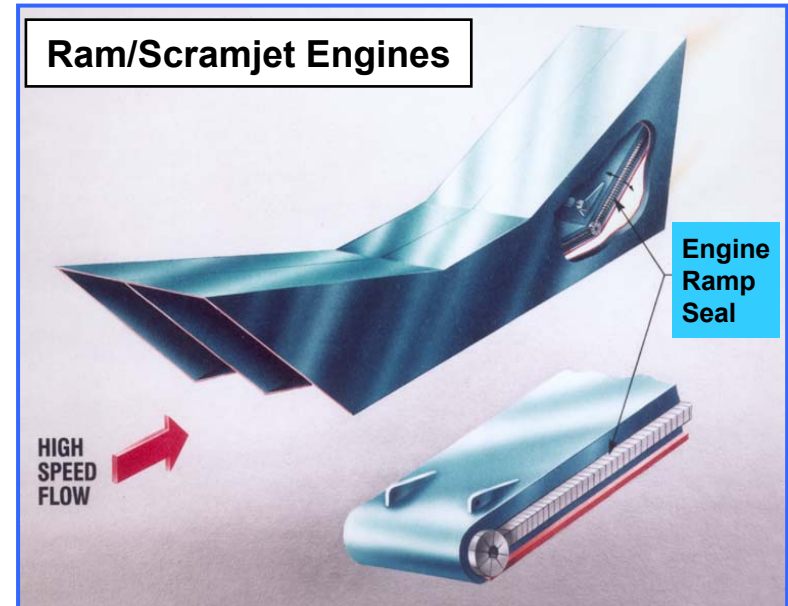
# Seal Design Requirements

## Paramount Goal:

- Prevent hot engine flow-path gases and potentially explosive fuel-rich mixtures from leaking past the seal system.

## Seal Design Requirements

- Withstand gas temperatures of 4000+°F and high heat fluxes. Operate at 1500-2500+°F with minimal cooling
- Limit leakage of hot gases and unburned propellant into backside cavities
- Survive in chemically hostile environment (e.g., oxidation, hydrogen embrittlement)
- Seal distorted sidewalls and remain resilient for multiple heating cycles
  - Flat engine sidewalls distort under pressure
- Survive hot scrubbing with acceptable change in flow rates
- Resist high vibration and acoustic (150+dB) levels





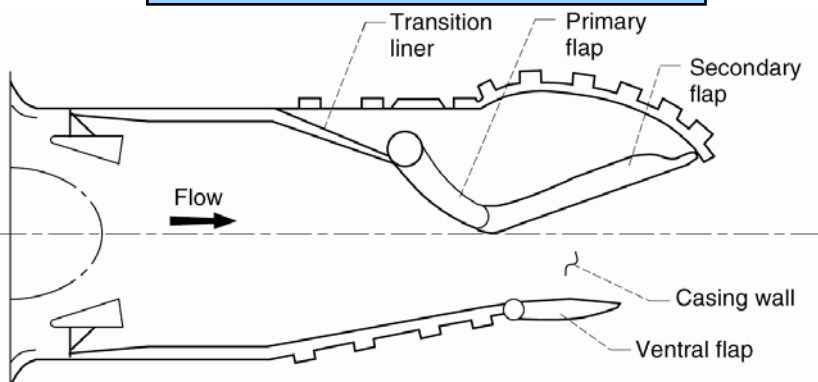
# Establishing Propulsion Seal Design Requirements

- Leakage Limits -- Generally thermally driven with the following considerations:
  - Inlet:
    - Prevent aerodynamic loss/drag and
    - Prevent overheating of hinge and drive mechanisms
  - Combustor/Nozzle:
    - Coolant flow rate: seals may be used to limit coolant flow into combustion chamber
    - Thermal: prevent leakage of potentially damaging high temperature gases into backside cavities
    - Safety: prevent unburned fuel (e.g. hydrogen, etc) from reaching backside cavities
- Temperature, Pressure
  - Establish with propulsion system analysts and thermal/structures communities
  - Varies with engine mode (ram/scramjet, etc.), ramp position, vehicle trajectory, dynamic pressure, angle of attack, etc.
  - “Un-start” pressures can be several fold higher than nominal operating pressure
    - Determine seal performance requirement during and after “un-start” condition.
- Gap Change:
  - Caused by differential expansion rates of adjoining structures
  - Establish with thermal/structures community
- Life: Driven by system level requirements
  - Anticipated stroke both large and “dithering” per mission → multiplied by number of missions.

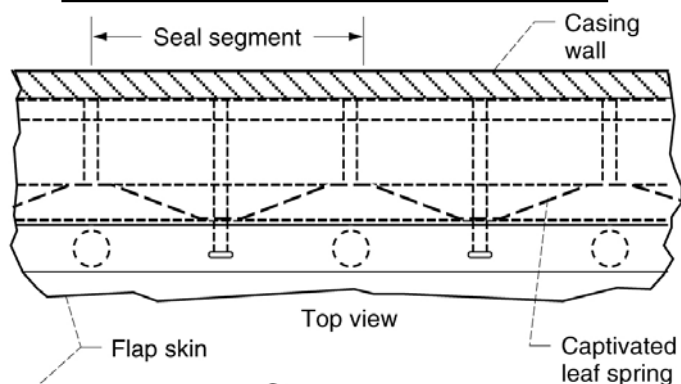
# **Seal concepts**

# Heritage Turbojet 2-D Nozzle Seals

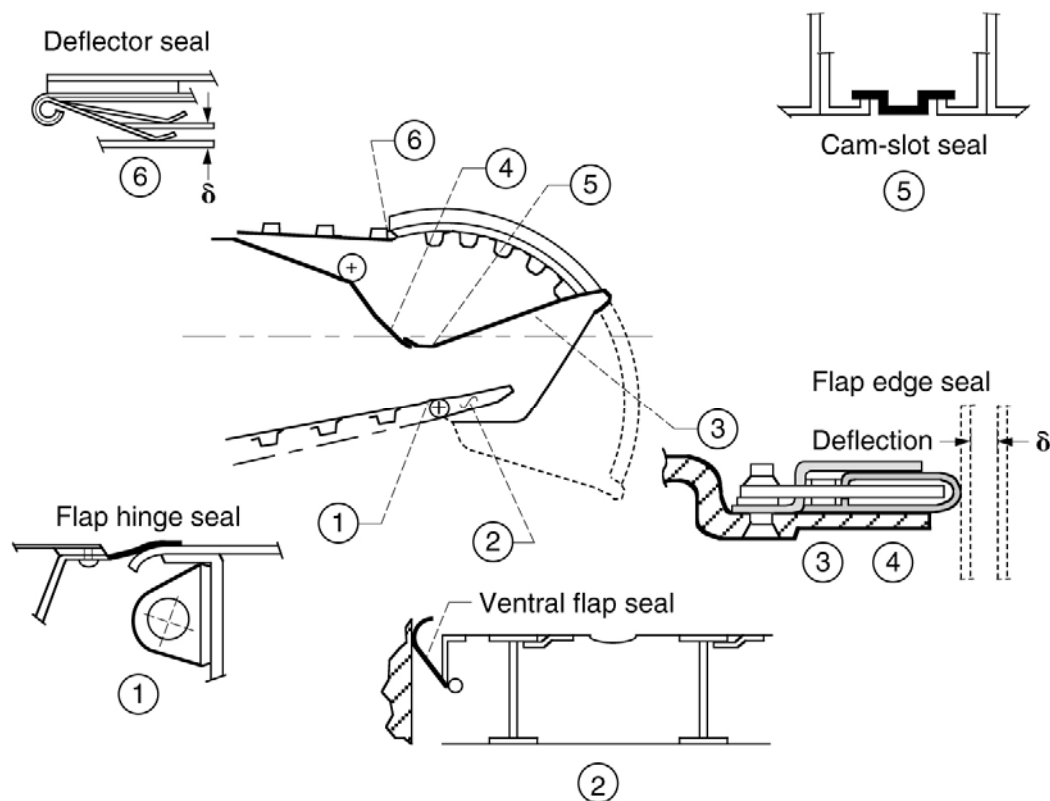
## 2-D Nozzle Cross-Section



## Flap Edge Seal Top View



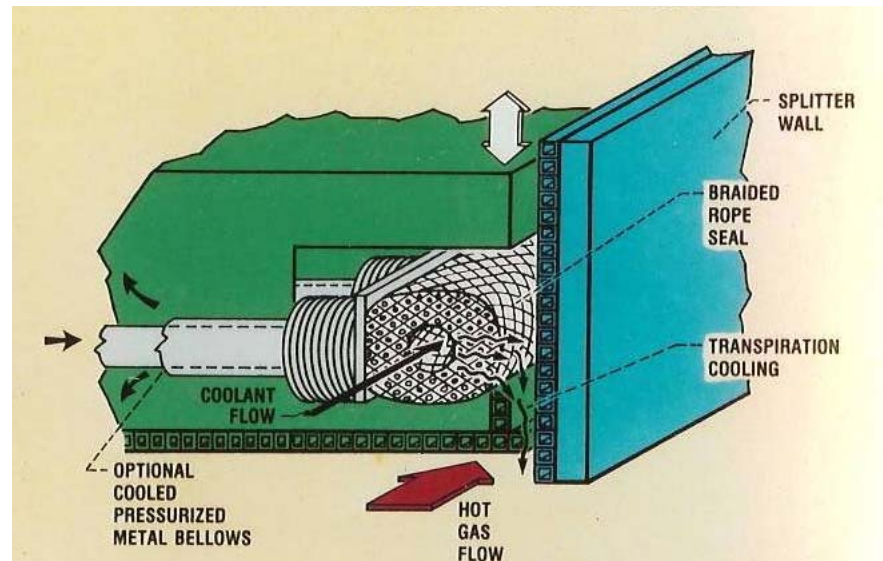
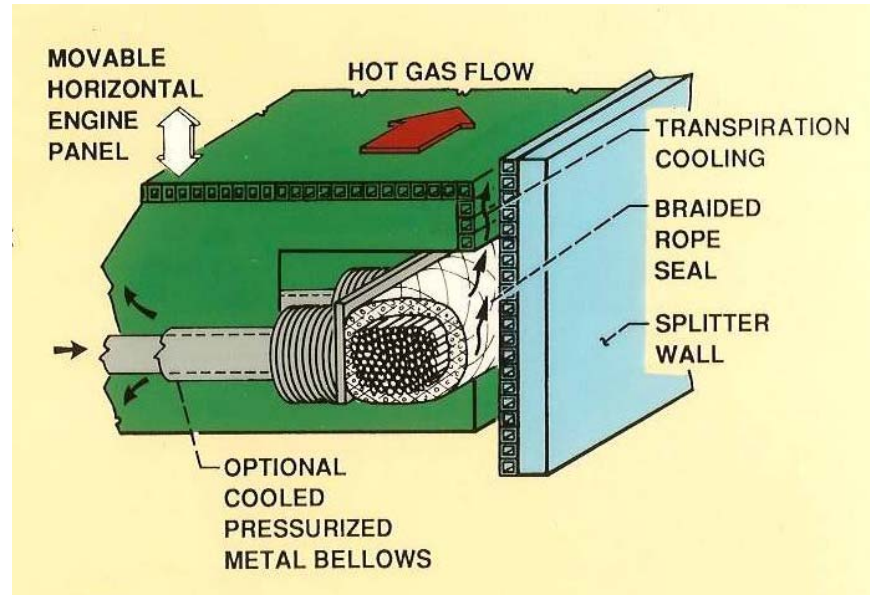
## Candidate Seal Cross Sections



- 2-D Nozzle seals can be used for lower Mach number engine duct seals
  - Operating temperature 1200-1500+F, depending on material and time at temperature.
  - Superalloy materials: Inconel 625, 718, X-750, Waspalloy, Rene-41

# Braided Rope Seals

- Design Attributes:
  - High temperature, high pressure operation (with high degree of longitudinal fibers)
  - Conformability to distorted walls
  - Good for static or low sliding distance/speed applications
  - Compact packaging
  - Internal passageway possible via braiding permitting transpiration cooling (lower figure)
- Issues:
  - Ceramic fibers damage easily
    - With scrubbing
    - With high acoustic/vibratory loading
    - Remedy: requires metal sheath (thereby limiting temperatures for sliding application)
  - For large gap changes some form of preload system is required
  - Porosity is high unless high degree of longitudinal fibers



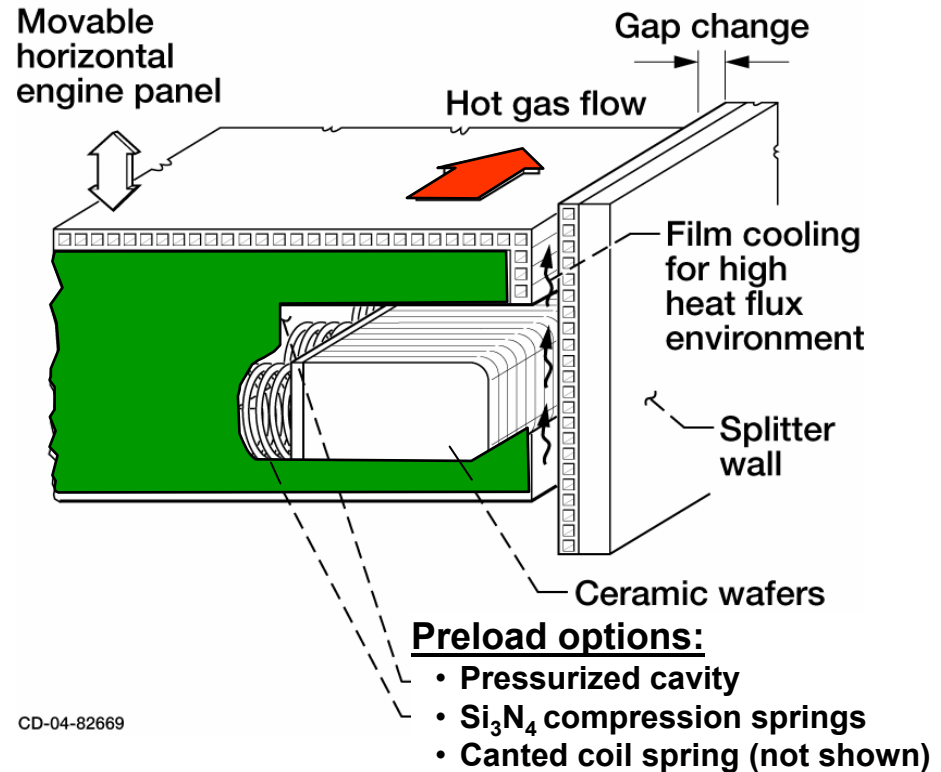
# Wafer Seals

## ◆ Attributes:

- ◆ Potential for very high temperature service (2300+°F)
- ◆ Flexibility through sliding of adjacent wafers
- ◆ Very low leakage rates
- ◆ Excellent durability

## ◆ Considerations:

- ◆ Ceramic wafers may damage very thin heat exchanger walls → requires testing
- ◆ Ceramic wafers have lower coefficient of thermal expansion than metals → check  $\Delta$  axial growth for design.



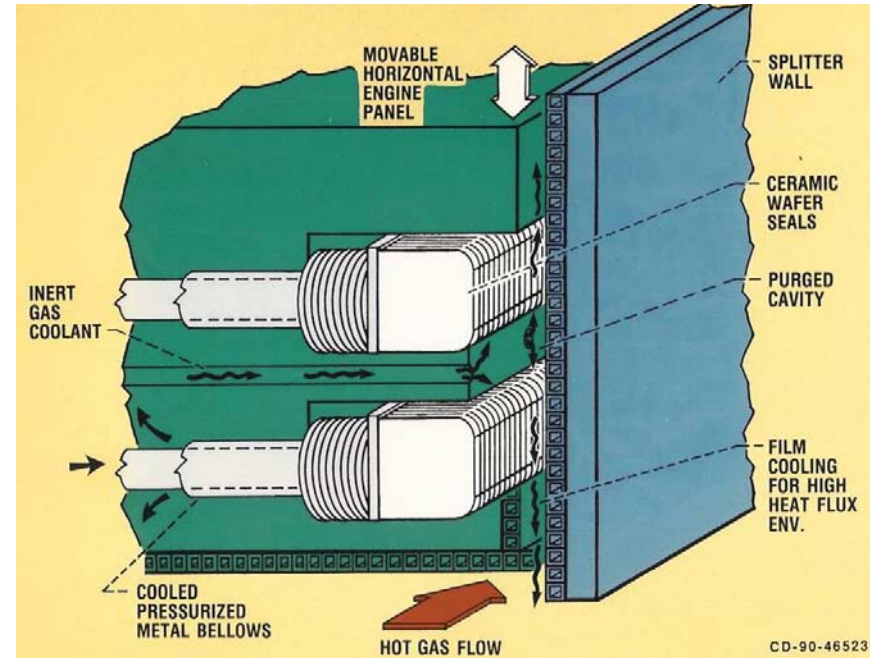
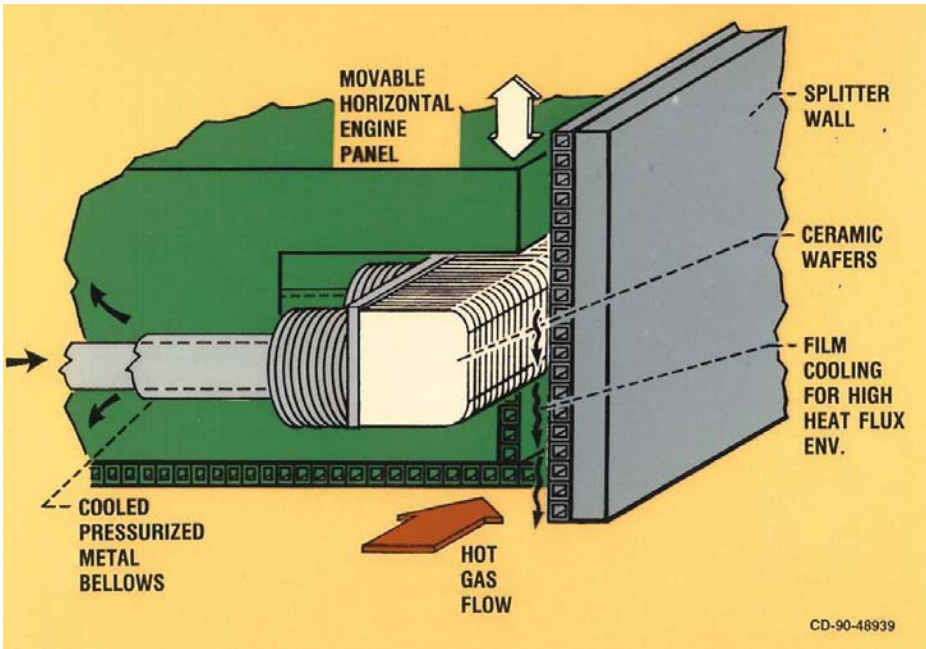
## ■ Baseline wafer design:

- Materials: monolithic silicon nitride (Honeywell AS800)
  - Can also be made of other ceramic/superalloy materials
  - Size: 0.5" wide x 0.92" long x 0.125" thick

## ■ Baseline Preloader:

- $\text{Si}_3\text{N}_4$  compression springs

# Wafer Seal: Alternate Embodiments



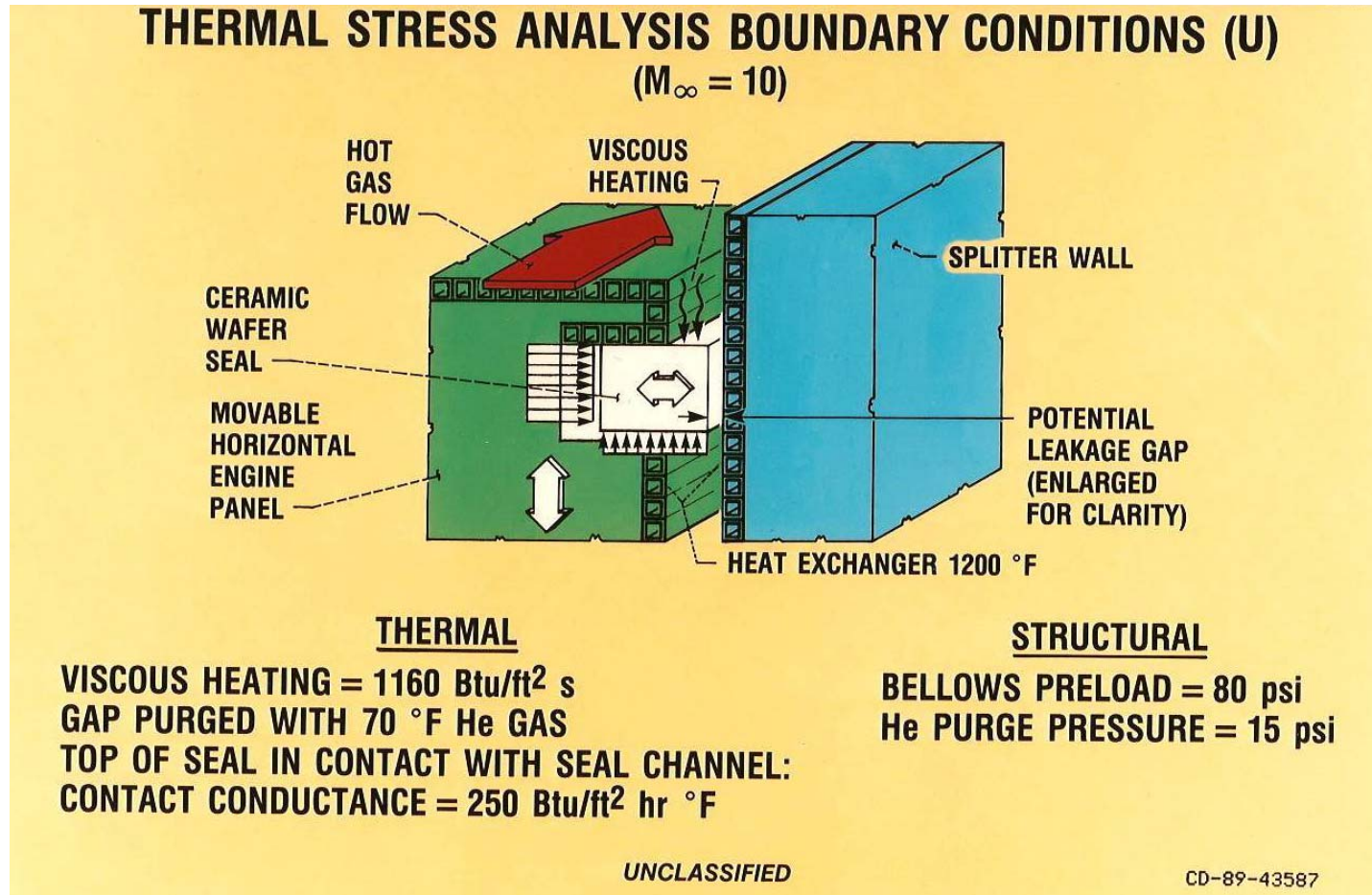
- Alternate Preloader Approach
  - Cooled, pressurized metal bellows

- Centrally purged/redundant design:
  - Cavity pressurized above local flow path pressure
    - Cools seal for flow-path temperatures above 2300-2500°F
    - Provides back-flow pressure margin without pressurizing entire back side cavity



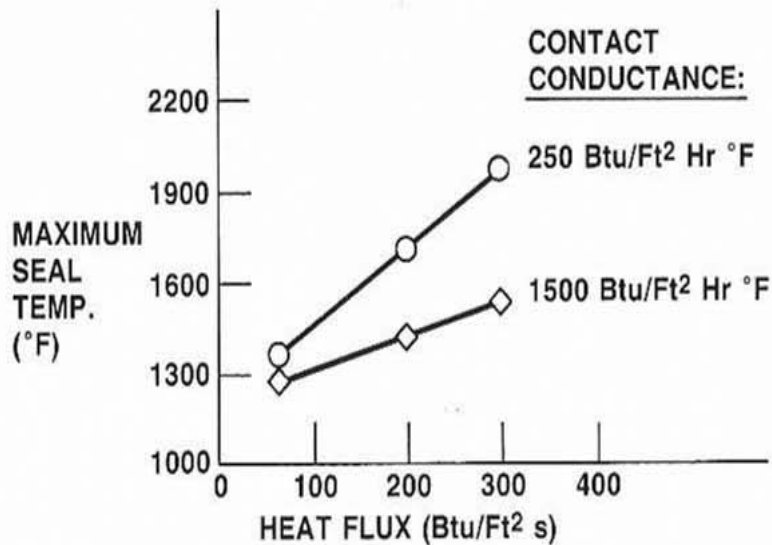
# **Seal Thermal Analysis Mach 10 Propulsion System**

# Ceramic Wafer Seal Thermal Analysis Boundary Conditions (U)

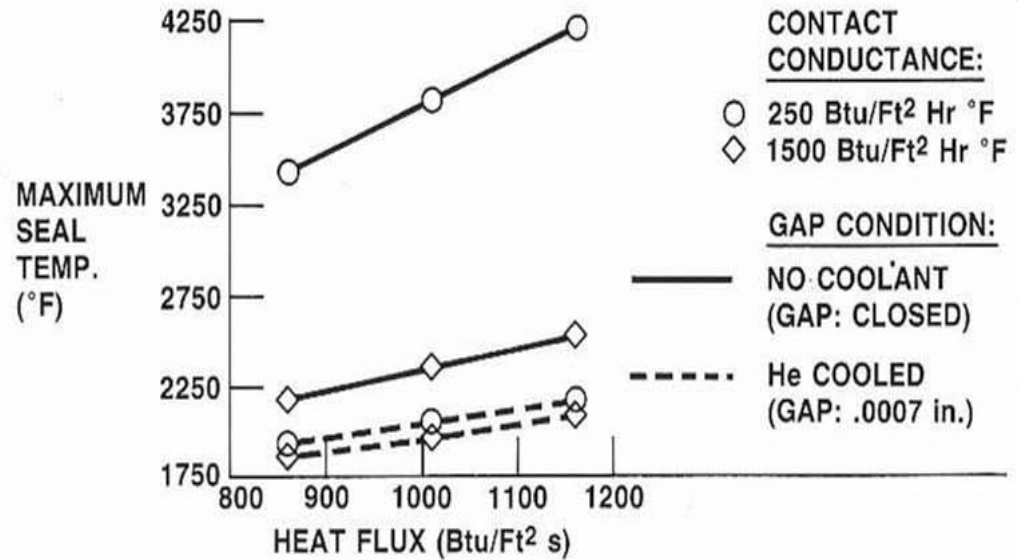


- Assessed ceramic wafer seal thermal response for Mach 10 free-stream condition in NASP engine inlet and combustor.
- Seal (silicon carbide wafers) cooled with Helium purge in combustor

# Ceramic Wafer Seal Thermal Analysis Results



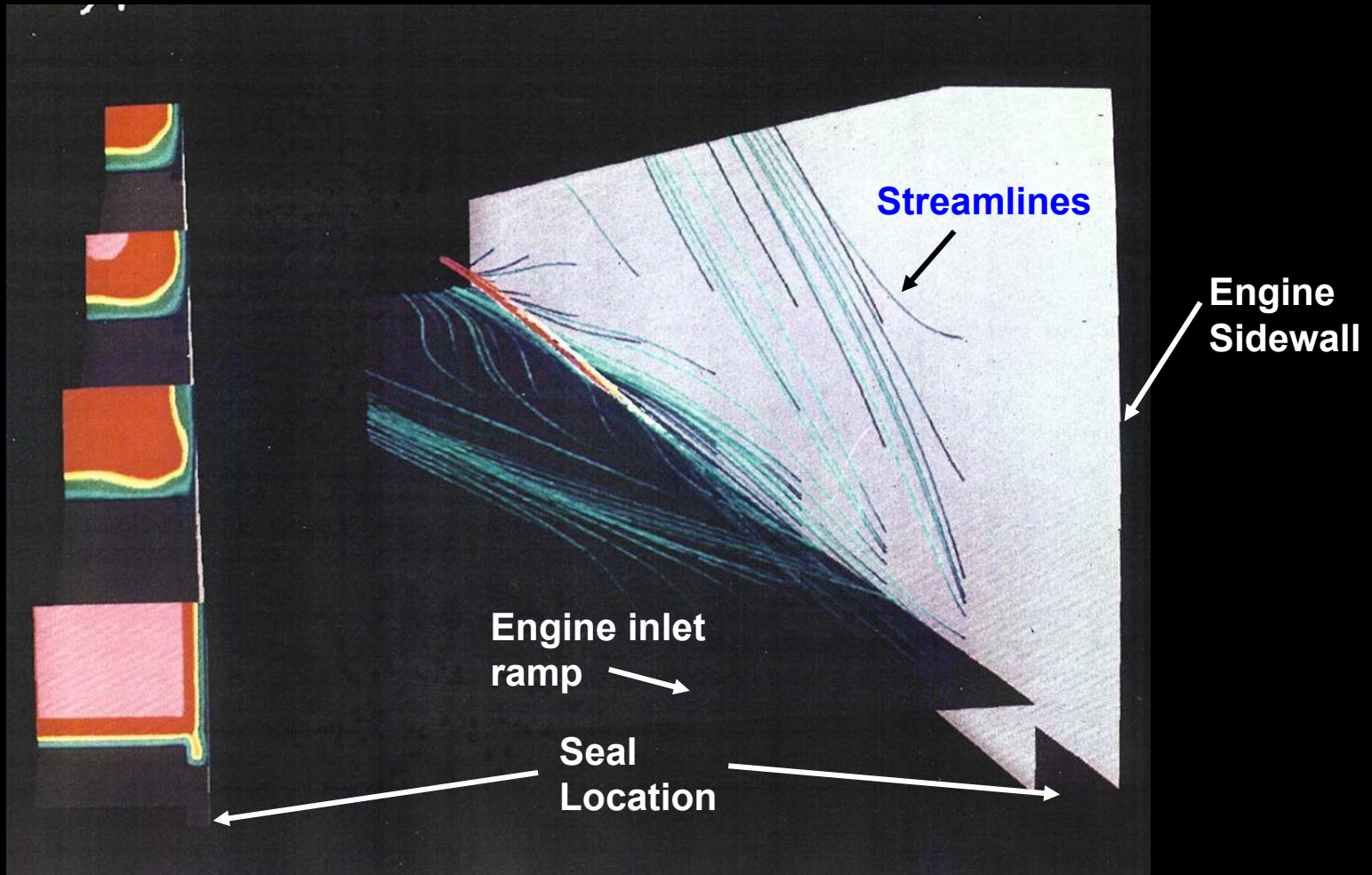
(A) MAXIMUM SEAL TEMPERATURE FOR ENGINE INLET HEAT FLUX RATES FOR TWO SURFACE CONTACT CONDUCTANCES. GAP CLOSED



(B) MAXIMUM SEAL TEMPERATURE FOR COMBUSTOR ENTRANCE REGION HEAT FLUX RATES FOR TWO SURFACE CONTACT CONDUCTANCES.

- Inlet seal: stayed below 2500°F w/o Helium coolant
- Combustor seal: seal required Helium coolant for lower assumed contact conductance with channel

# Hypersonic Gap Simulation

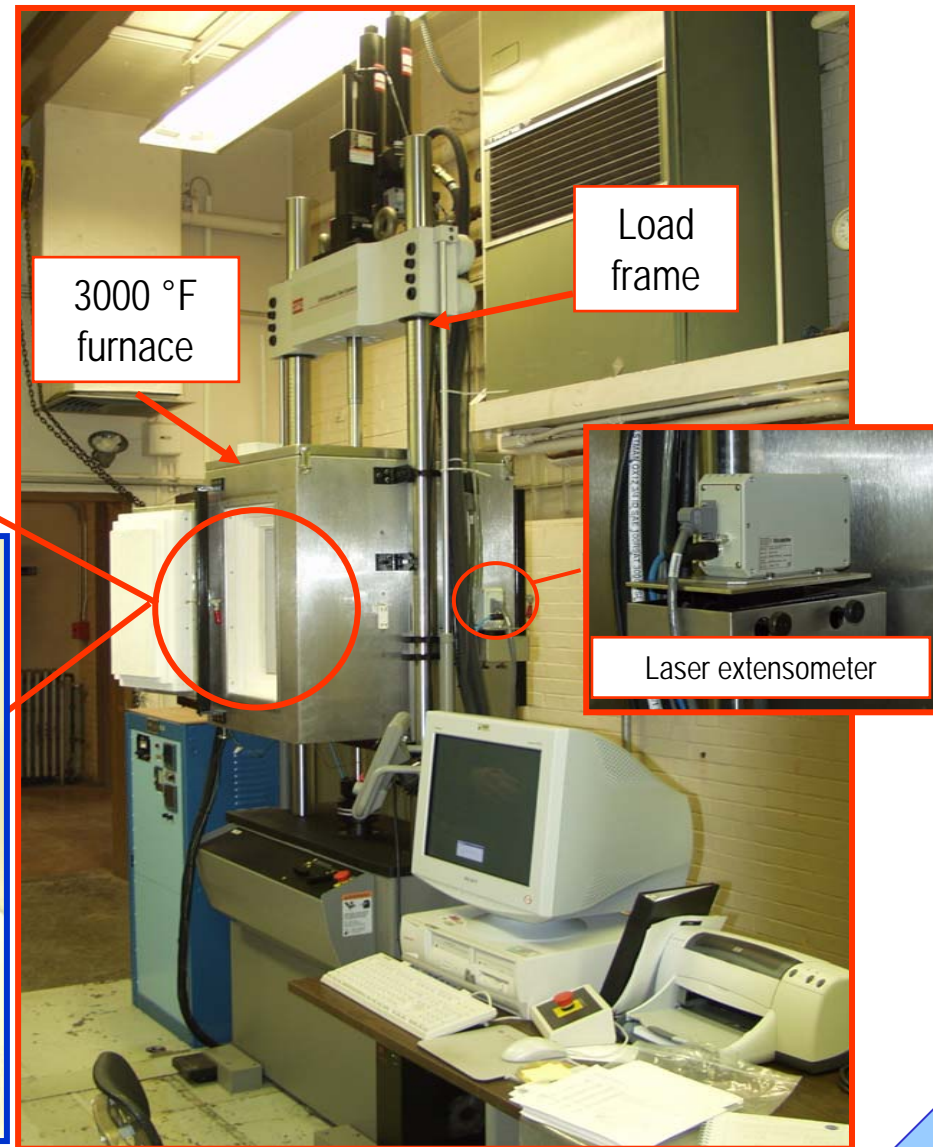
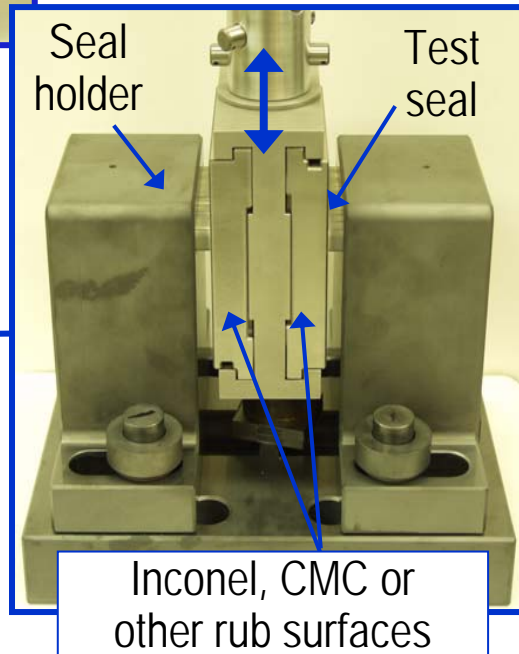
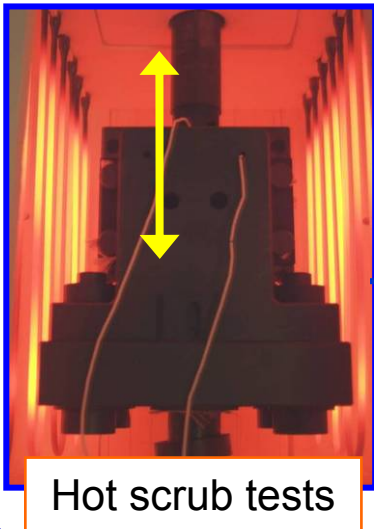
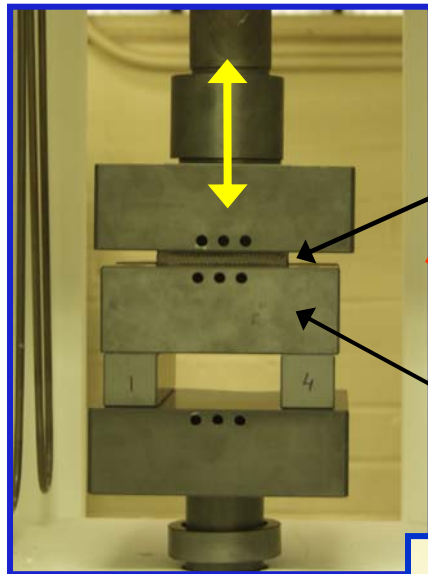


- Performed CFD solutions of inlet seal to examine heating rates/flow in seal cavity.
  - Near cowl lip: high heating rates in groove
  - Down-stream, high speed flow is swept out of groove reducing local heat transfer
  - Shock interaction effects can greatly increase local structural and seal heating rates.
    - Weak interaction: 1.25 multiplier; Strong interaction 5.5 multiplier

# **NASA GRC Test Capabilities to Evaluate Advanced Seal Concepts**

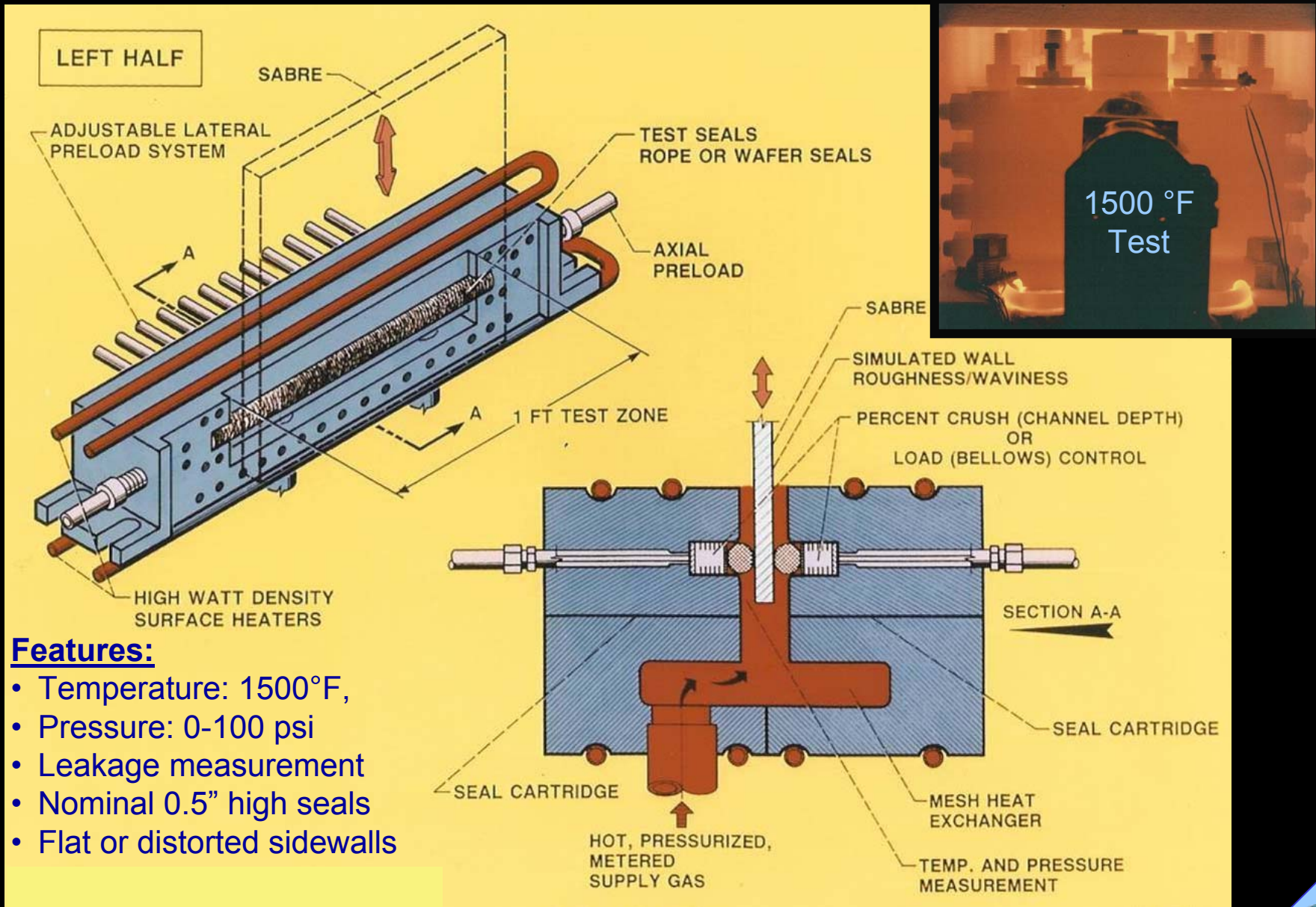


# GRC Hot Compression/Scrub Seal Test Rig: Overview





# High Temperature Dynamic Flow Test Fixture

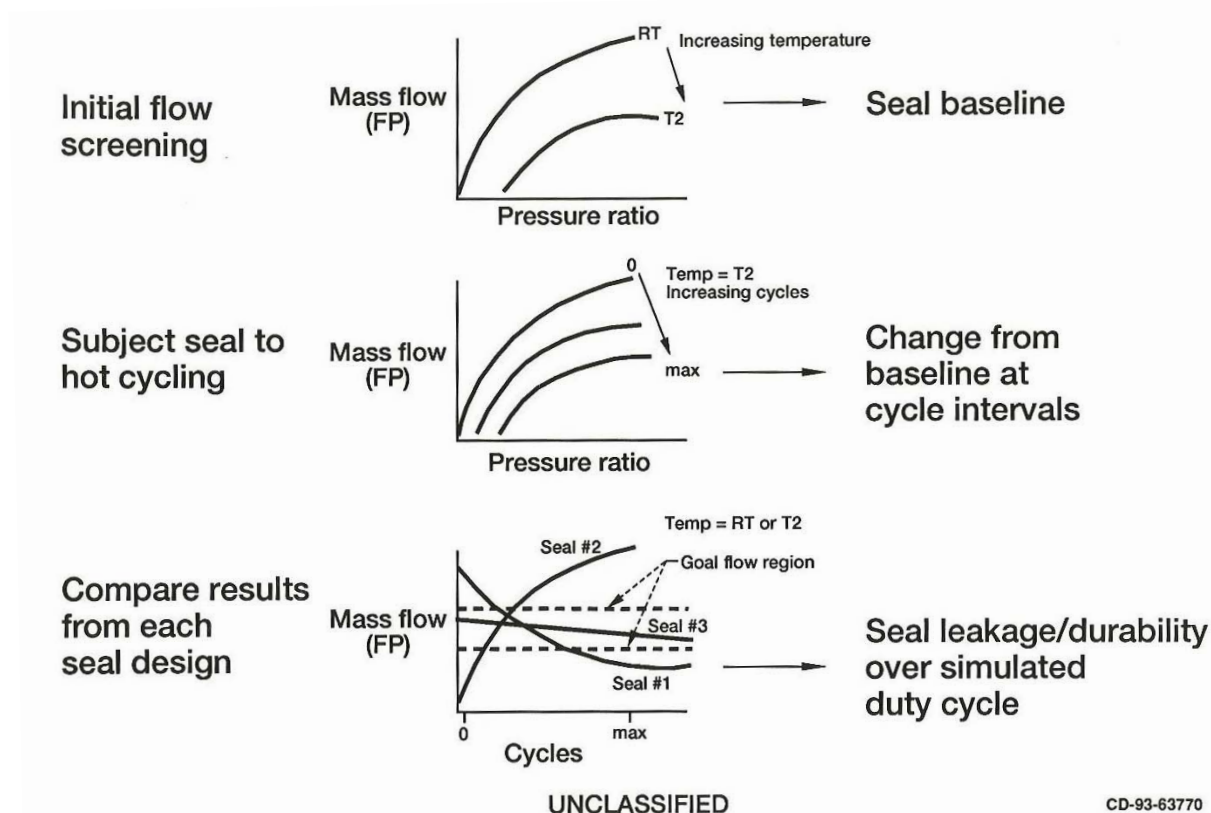


## Features:

- Temperature: 1500°F,
- Pressure: 0-100 psi
- Leakage measurement
- Nominal 0.5" high seals
- Flat or distorted sidewalls

**Seal Performance Assessments**  
**Case Study #1**  
**Braided Rope Seals**

# Roadmap for Seal Development: Balancing Conflicting Requirements



- Goal: Develop flexible seal that exhibits satisfactory
  - Pressure blocking: withstand 100+ psid
  - High temperature durability: adequate life for application
  - Flow (prefer limited flow change with cycling):
    - Used as seal: low flow → to prevent excessive leakage,
    - Used as coolant limiter: adequate flow → to support transpiration cooling

# Braided Rope Seal: Experimental Parametric Study

Seal	Core				Sheath					
	Material <sup>a</sup>	Denier	Number of yarns	Core area, percent	Material <sup>a,b</sup>	Denier	Filament diameter		Number of layers	Number of filaments or yarns per tow
							$\mu\text{m}$	in.		
Hybrid:										
HY1	NX312	600	4400	98.4	HS188	110	40	0.0016	1	5
HY2	NX312	600	4400	95.1	HS230	688	100	.004	1	5
HY3	NX312	600	4400	94.8	HS25	172	50	.002	1	10
M1	NX440	700	3166	94.4	IN600	569	100	.004	1	5
All-ceramic:										
AC1	NX312	600	4000	83.0	NX550	2000	12	0.00048	2	2

<sup>a</sup>Ceramic fiber composition by weight percentage:

NX312 (Nextel 312): 62 Al<sub>2</sub>O<sub>3</sub>, 24 SiO<sub>2</sub>, 14 B<sub>2</sub>O<sub>3</sub>

NX440 (Nextel 440): 70 Al<sub>2</sub>O<sub>3</sub>, 28 SiO<sub>2</sub>, 2 B<sub>2</sub>O<sub>3</sub>

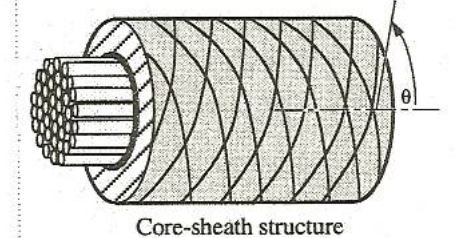
NX550 (Nextel 550): 73 Al<sub>2</sub>O<sub>3</sub>, 27 SiO<sub>2</sub>

<sup>b</sup>Metal wire composition by weight percentage:

IN600 (Inconel 600): 76 Ni, 15.5 Cr, 8.0 Fe, 0.5 Mn, 0.2 Si, 0.08 C

HS25 (Haynes 25): 46 Co, 21 Cr, 16 W, 11 Ni, 3 Fe, 2 Mn, 1 Si, 0.05 C

HS188 (Haynes 188): 38 Co, 22 Cr, 14 W, 3 Fe, 1.25 Mn, 0.5 Si, 0.08 La, 0.015 B, 0.05 C



**Core:** Nextel 312, fiber diameter, 8  $\mu\text{m}$   
**Sheath:** 24 carriers, braid angle 80°

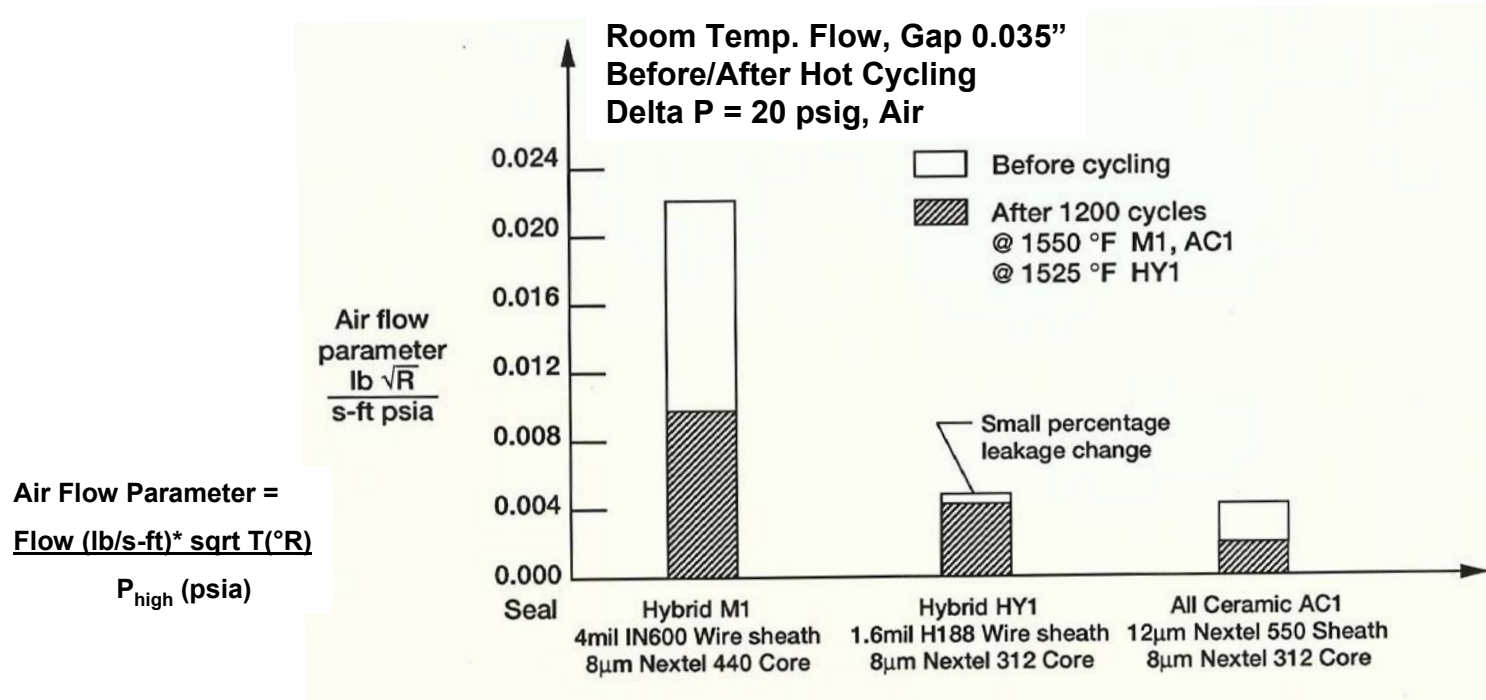
## Nomenclature:

- **AC:** All Ceramic
- **HY:** Hybrid – ceramic core and superalloy sheath for improved durability

- Seal specimens constructed of uniaxial ceramic core fibers (low porosity) and various sheath materials to evaluate flow and durability after room and high temperature (1500+°F) scrubbing
- Core and sheath parameters selected to minimize seal leakage
  - High braid angle
  - Minimum sheath thickness

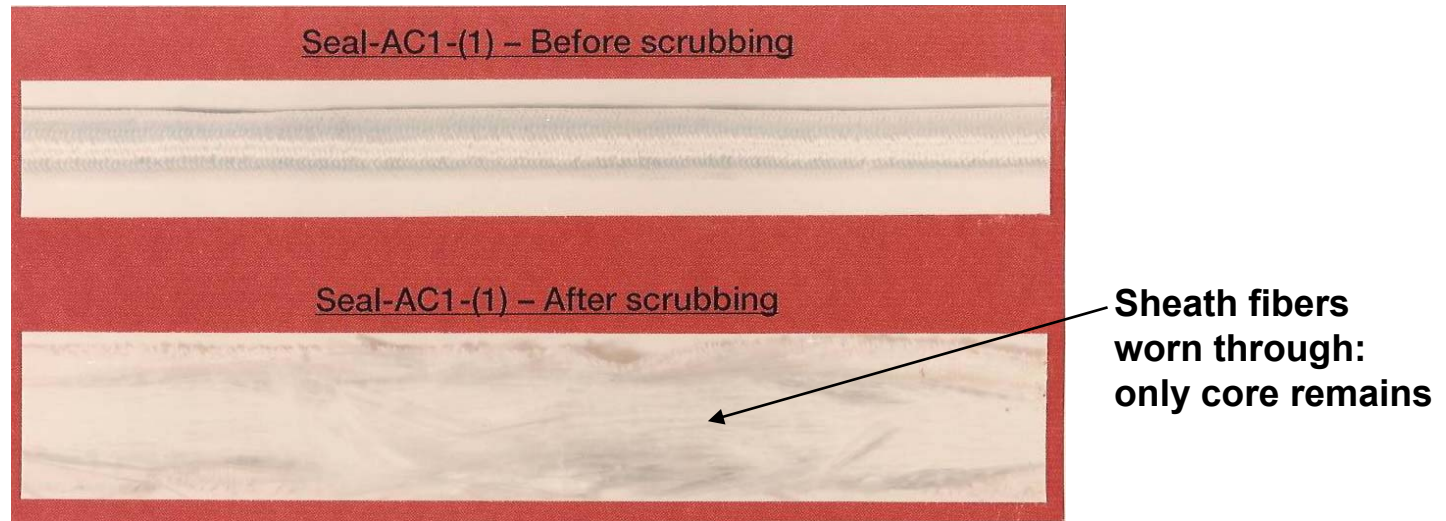


# Comparison of Rope Seal Leakage Rates Pre- and Post- 1525+°F cycling



- Hybrid seal performance dependent on wire diameter
  - Larger wire sheath (M1) seals resulted in higher leakage and greater variability with cycling than smaller wire sheath (HY1)
  - Hybrid HY1 (1.6 mil wire diameter) and Hybrid HY3 (2 mil wire diameter) exhibited flow rates in line with thermal requirement
  - Larger wire sheath seals exhibited better durability (see photographs)
- All-ceramic (AC1) seals performance
  - Exhibited lowest leakage of braided seals but significant variation with cycling
  - Exhibited worst durability (see photographs)

# All-Ceramic Braided Rope Seal Durability Results

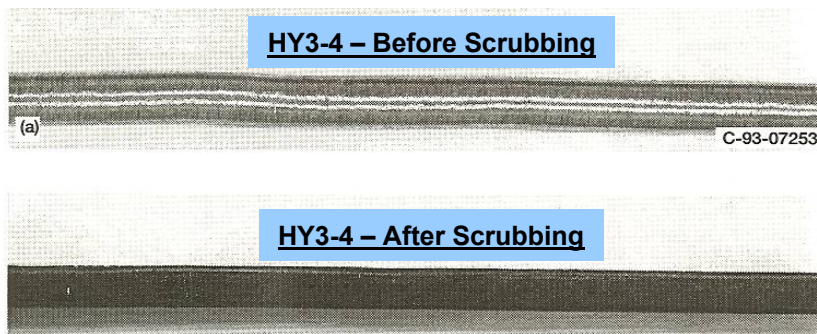
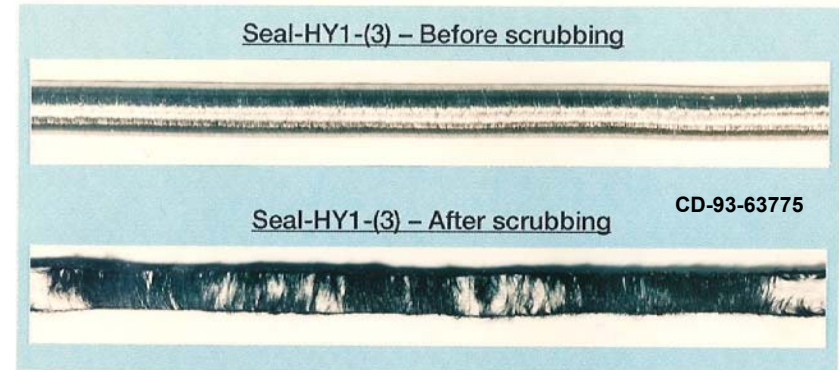
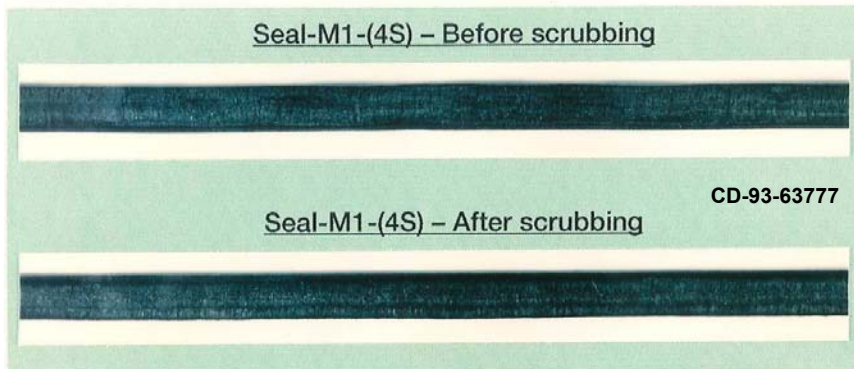


Seal sheath material and test temperatures for 4800 in. scrubbing.

- Nextel 550 sheath, 1550°F
    - Previous studies showed Nextel 550 tow durability better than Nextel 312 or Nextel 440
  - Scrub Surface: Inconel X-750,  $\leq 32 \mu\text{in.}$
- 
- All Ceramic (AC1) seal completed 4800 in. of scrubbing with extensive damage
  - Nextel fibers are flexible and capable of high temperature but exhibit poor scrubbing performance against smooth rub surfaces.
    - Expect worse behavior against rough ceramic matrix composite (CMC) panels



# Hybrid Braided Rope Seal Durability Results



## Seal sheath materials and test temperatures for 4800 in. scrubbing.

- M1: 4 mil. Inconel 600 sheath wires, 1550°F
- HY1: 1.6 mil. HS188 sheath wires, 1525°F
- HY3: 2 mil Haynes 25 sheath wires, 1450°F
- Scrub Surface: Inconel X-750,  $\leq 32 \mu\text{in.}$

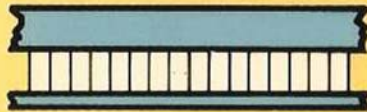
- M1 seal successfully completed 4800 in. scrub distance goal
- HY1 seal completed 4800 in. with some damage
- HY3 seal successfully completed 4800 in. scrub distance goal

**Seal Performance Assessments**  
**Case Study #2**  
**Wafer Seals**

# Ceramic Wafer Seal Flow: Effect of Wall Distortion

## METAL-BELLOWS PRELOAD SYSTEM (SEAL PRELOAD: 40 psi AVG.)

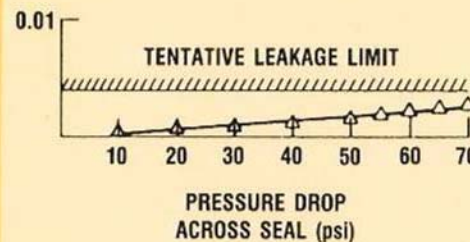
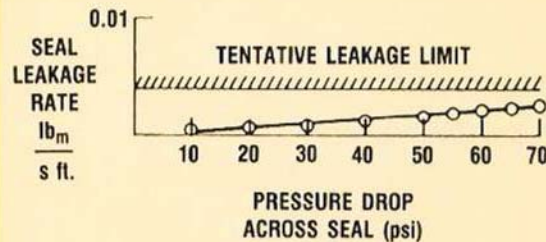
STRAIGHT WALL



DISTORTED WALL (1)



DISTORTED WALL (2)



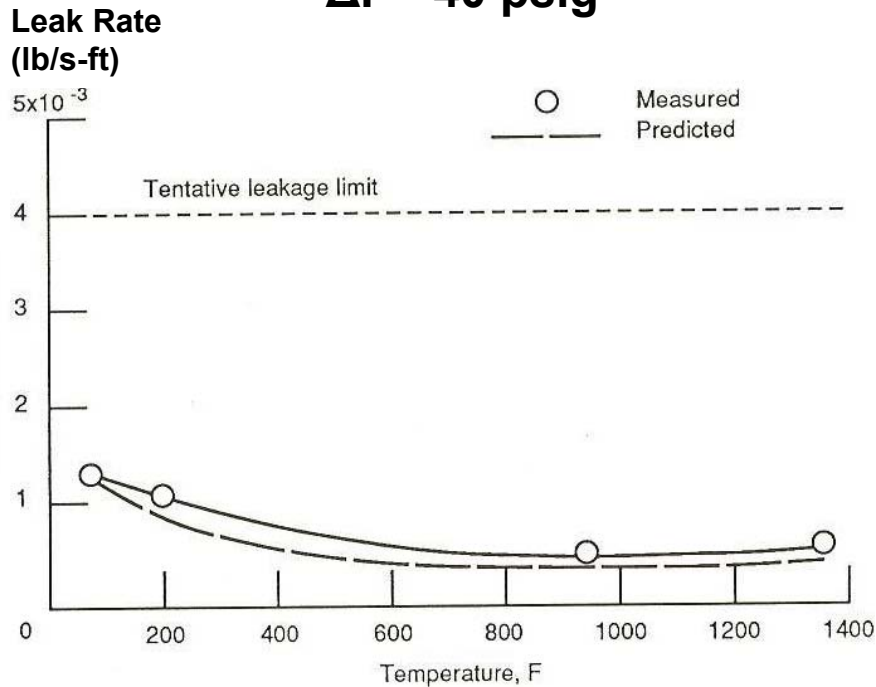
### Test Details:

0.5" square x 0.125" thick  $\text{Al}_2\text{O}_3$  wafers, metal bellow preloaders, 0.2" gap  
Ambient temperature air flow, static test

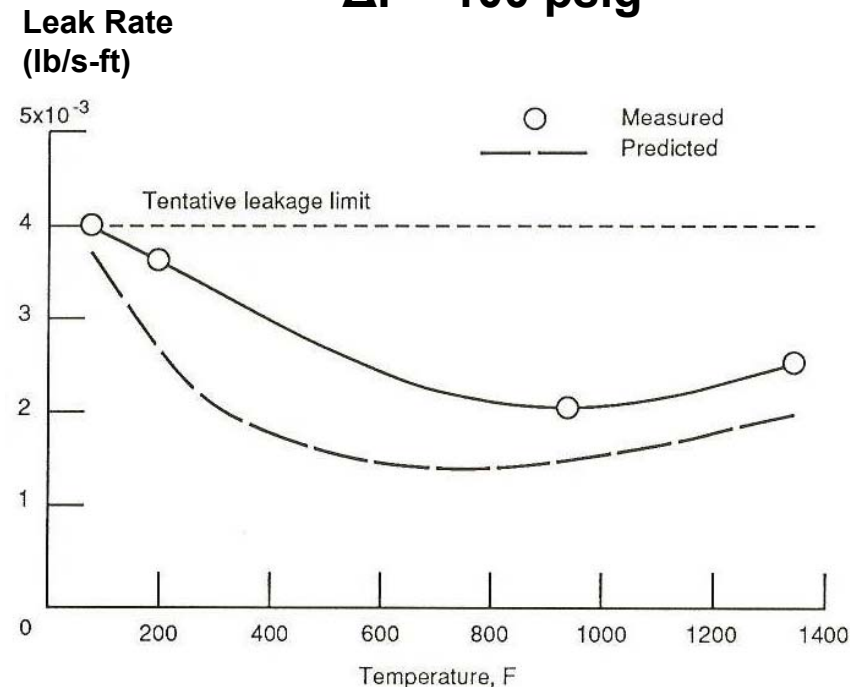
- Ceramic wafer seal effective at sealing either flat or distorted sidewalls

# Ceramic Wafer Seal Flow: Effect of Temperature

$\Delta P = 40$  psig



$\Delta P = 100$  psig



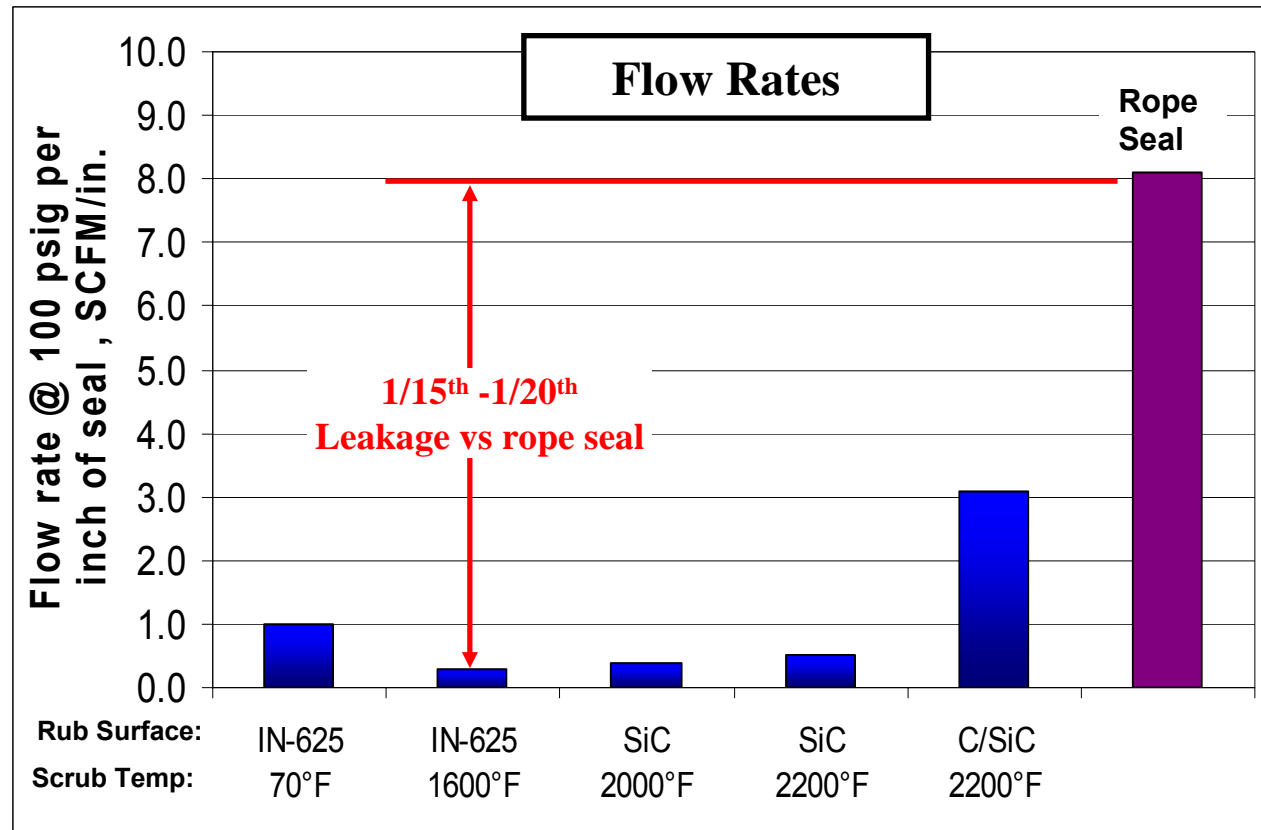
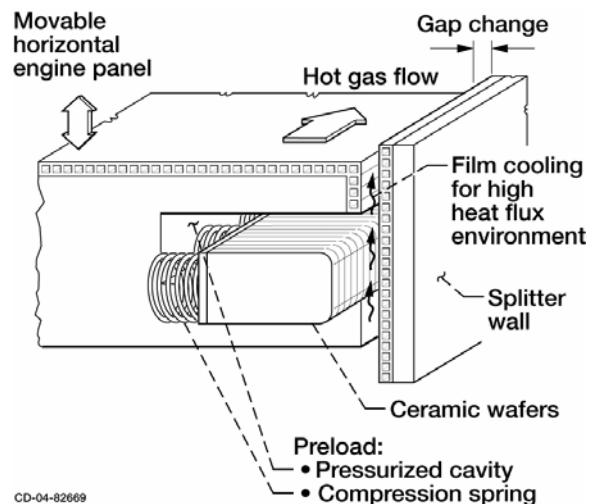
## Test Details:

0.5" square x 0.125" thick  $\text{Al}_2\text{O}_3$  wafers, metal bellow preloaders, 0.2" gap  
Air flow, static test (no sliding)

- Ceramic wafer seal effective sealing from room temperature through 1350°F
- Seal leakage decreases with increasing temperature → gas viscosity increases

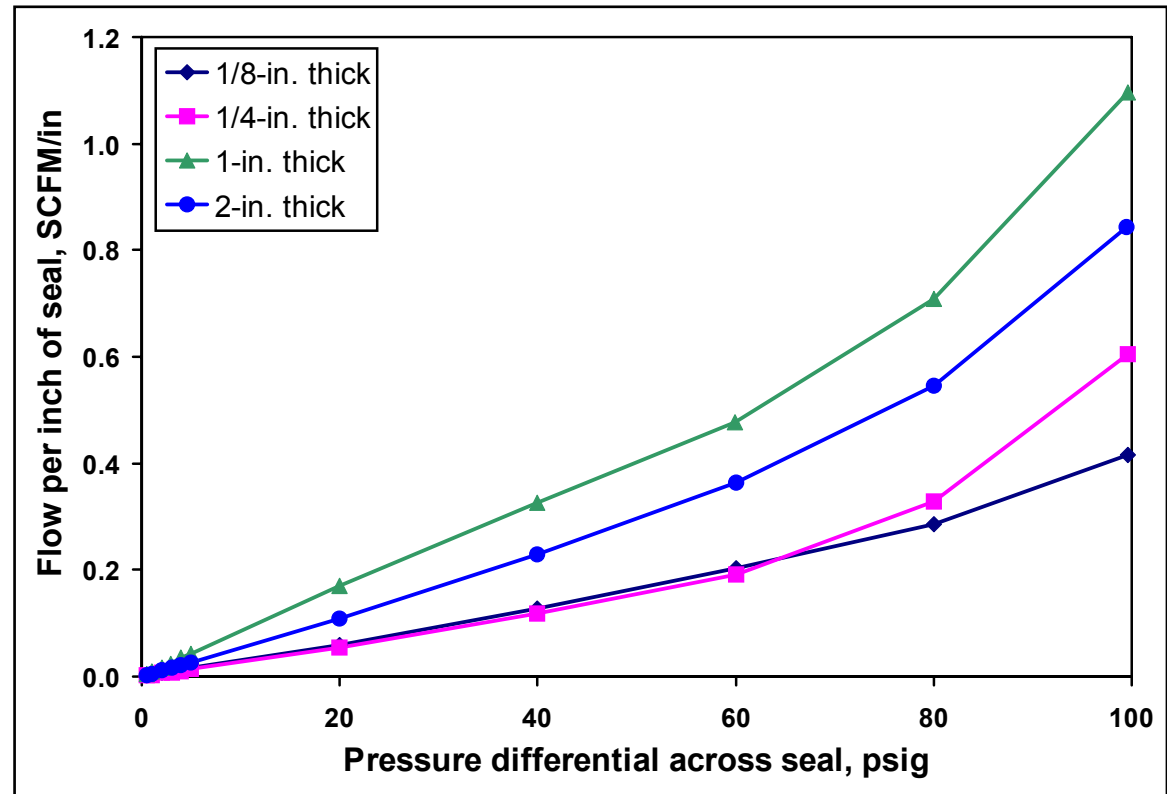
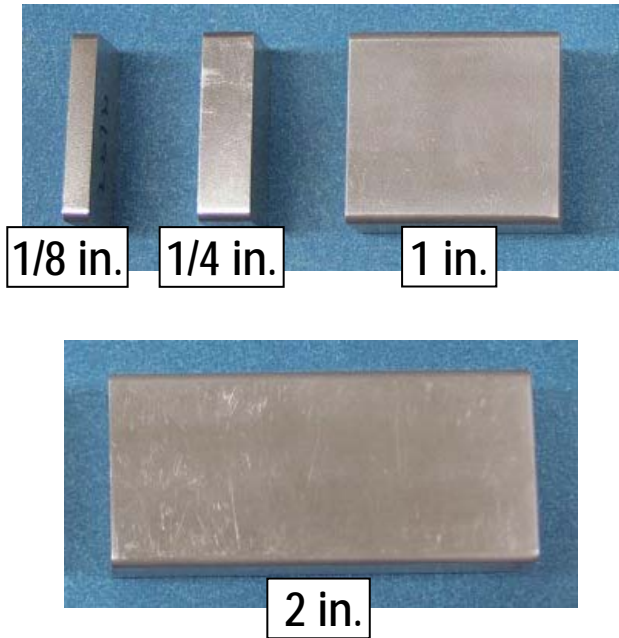
# Wafer Seal Flow vs. Candidate Wall Materials

- **Baseline wafer design:**
  - Material: monolithic silicon nitride (Honeywell AS800)
  - Size: 0.5" wide x 0.92" long x 0.125" thick
- **Baseline Preloader:**
  - $\text{Si}_3\text{N}_4$  compression springs



- ◆ **Wafer seal flow (R.T.) well behaved after ambient and 2200°F scrubbing against variety of candidate wall materials**
- ◆ **Wafer seal leakage after scrubbing 1/15-1/20<sup>th</sup> that of as-received braided rope seal at 100 psig.**

# Wafer Geometry Study: Thickness Variations

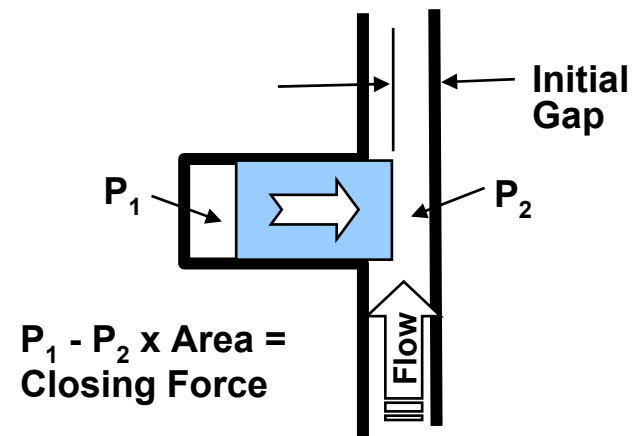
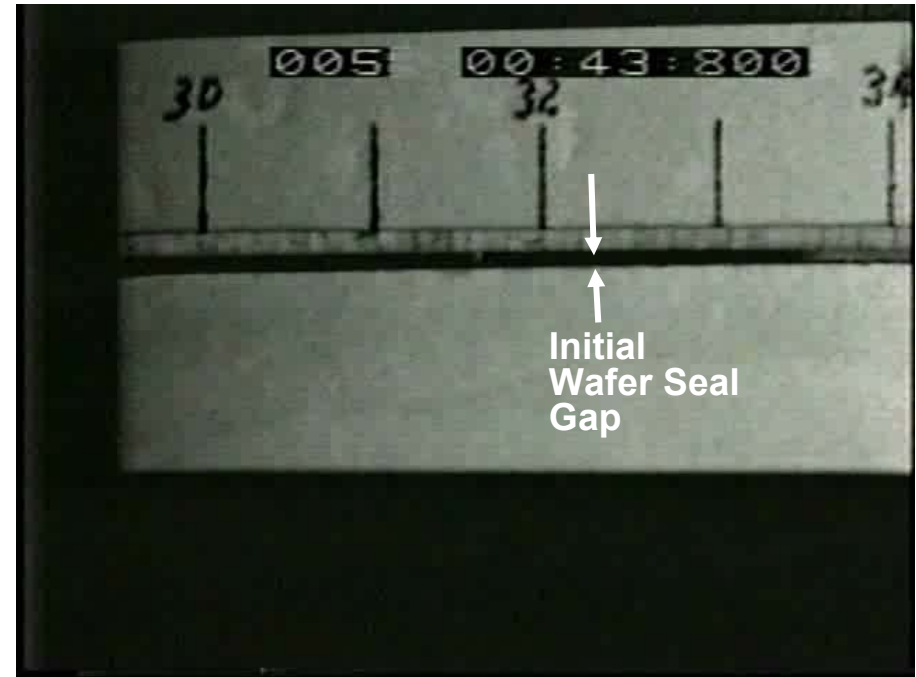


- Motivation: Thicker wafers have lower part count, fewer leakage paths
- Comparable leakage rates for 1/8-in. and 1/4-in. thick wafers: can reduce part count 2X by using 1/4-in. thick wafers
- Higher flow rates observed for 1-in. and 2-in. thick wafers
  - Less able to conform to sealing surface
  - However, 2" wafer flow still  $< 1/10^{\text{th}}$  rope seal flow at 100 psig



# Wafer Seal “Self-Sealing” Feature

- Wafer seals exhibit interesting “self-sealing behavior when exposed to engine level delta P (e.g. 100 psid)
- Test Conditions
  - Wafers started away from sealing surface ~0.1”
  - Pressure ramped from 0 to 100 psig
  - Wafers move via pressure-derived forces to close and seal the gap – no mechanical preloader
  - Video clip: 1/3 actual speed.



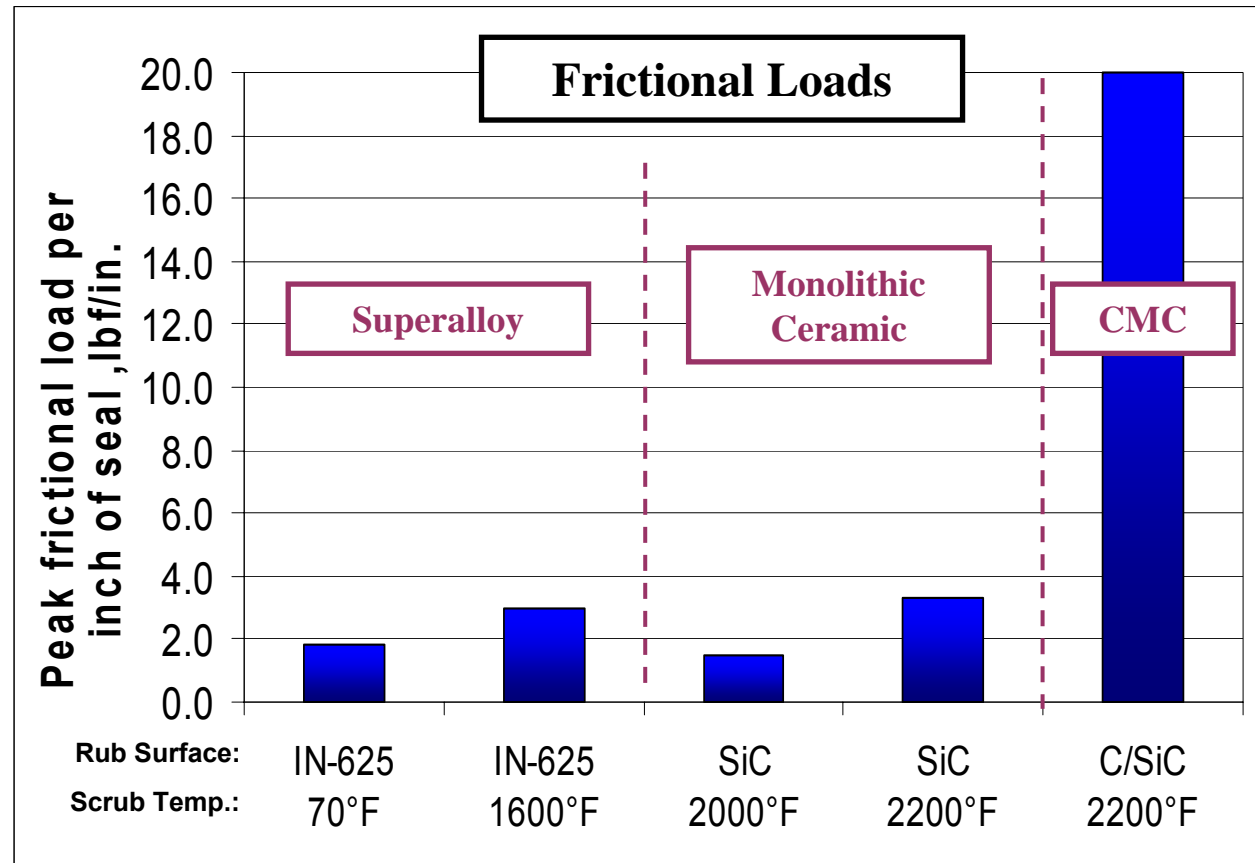
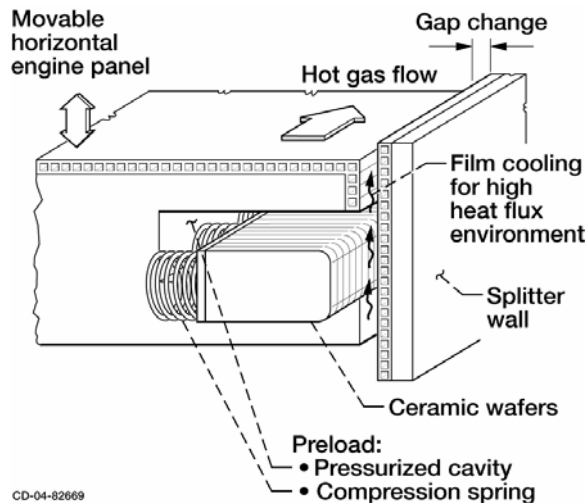
# Wafer Seal Friction Loads vs. Candidate Wall Materials

## ■ Baseline wafer design:

- Material: monolithic silicon nitride (Honeywell AS800)
- Size: 0.5" wide x 0.92" long x 0.125" thick

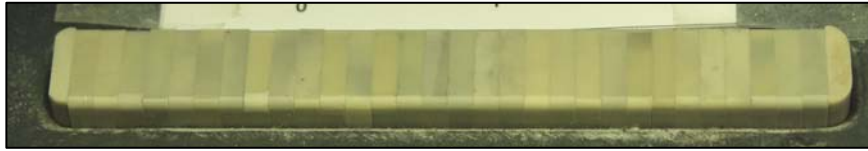
## ■ Baseline Preloader:

- $\text{Si}_3\text{N}_4$  compression springs

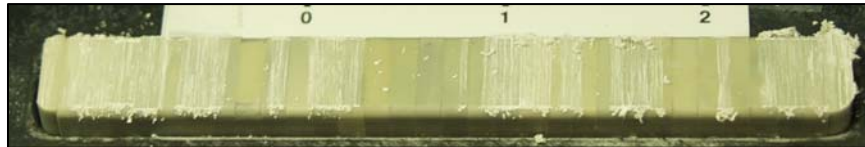


- ◆ Wafer seal friction loads were low against smooth Inconel 625 (to 1600°F) and Silicon Carbide (to 2200°F) rub surfaces
- ◆ Wafer seal loads increased substantially against Carbon/Silicon Carbide at 2200°F
  - ◆ May require solid lubricant coating to mitigate friction.

# Ceramic Wafer Seal Scrub Test Results vs. Ceramic Rub Surfaces



Wafer seals before 2200°F scrub test vs. SiC



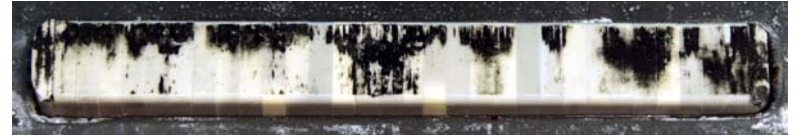
Wafer seals after 2000 in. of scrubbing at 2200°F vs. SiC



SiC panel after 2000 in. of scrubbing at 2200°F



Wafer seals before 2200°F scrub test vs. C/SiC



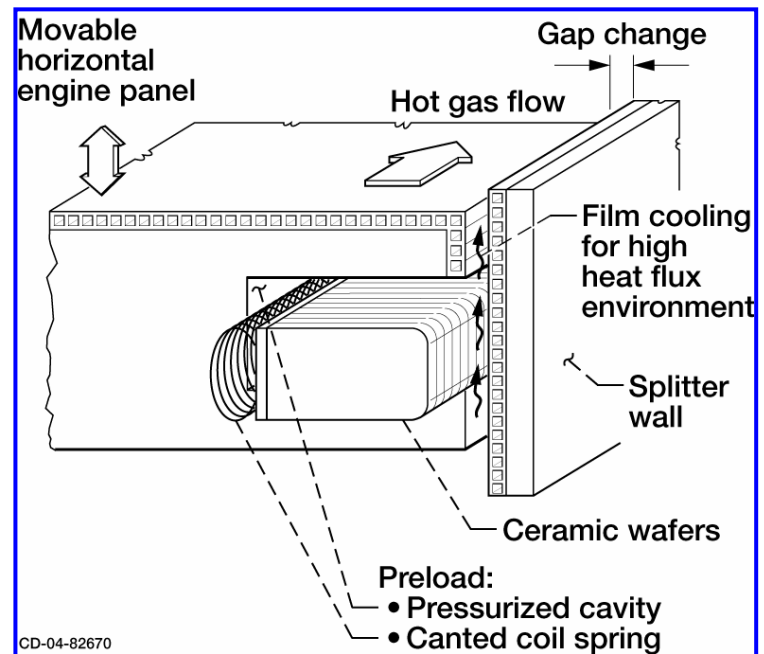
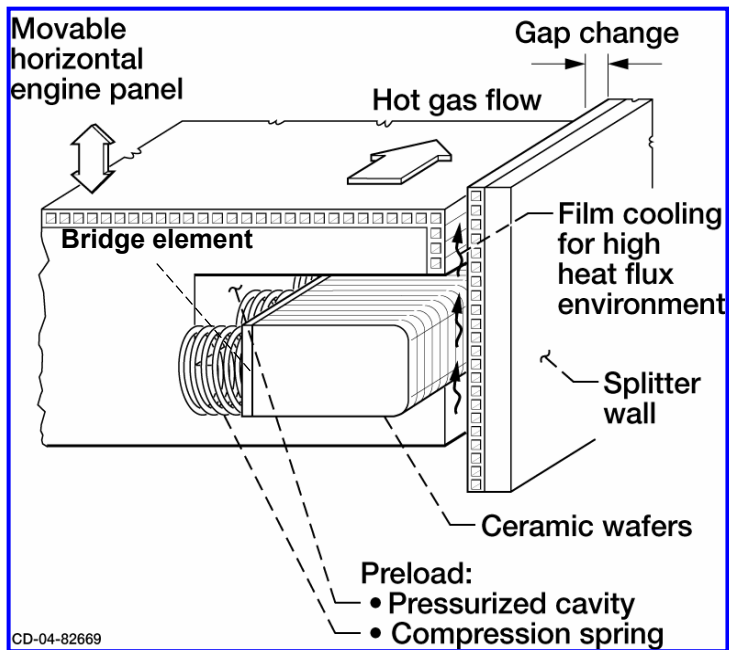
Wafer seals after 500 in. of scrubbing at 2200°F vs. C/SiC



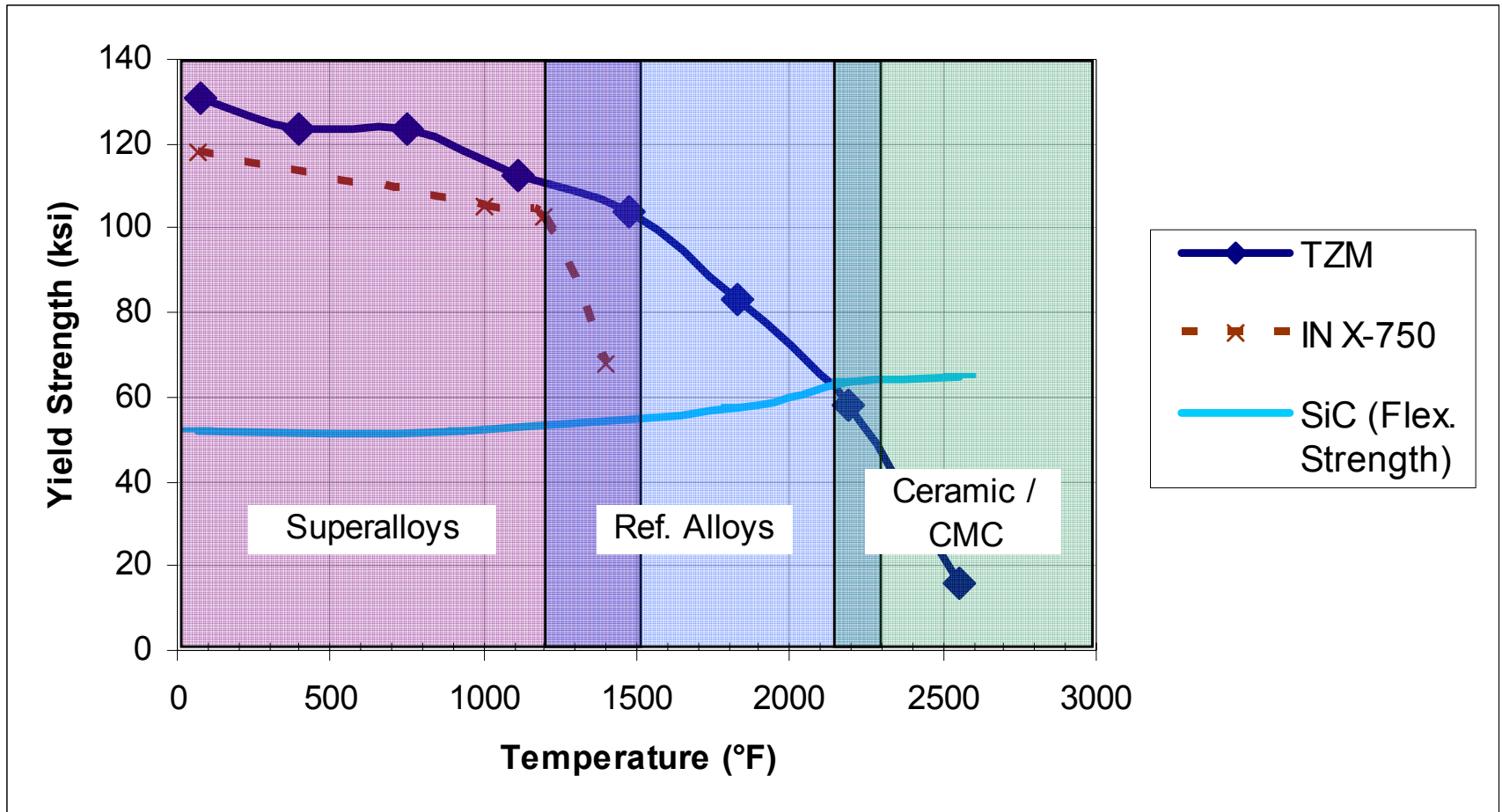
C/SiC panel after 500 in. of scrubbing at 2200°F

- Minimal damage to silicon nitride wafers during scrub testing
  - No chips in wafers
  - Black material from C/SiC built up on wafers during testing
  - Wafers much more durable vs. CMC rub surfaces than textile-based seals
- Debris on SiC rub surfaces after testing; believed due to abrasion of oxide layer
- Minor scuffing observed on C/SiC rub surfaces

# High Temperature Seal Preloader Development



# The Materials Challenge

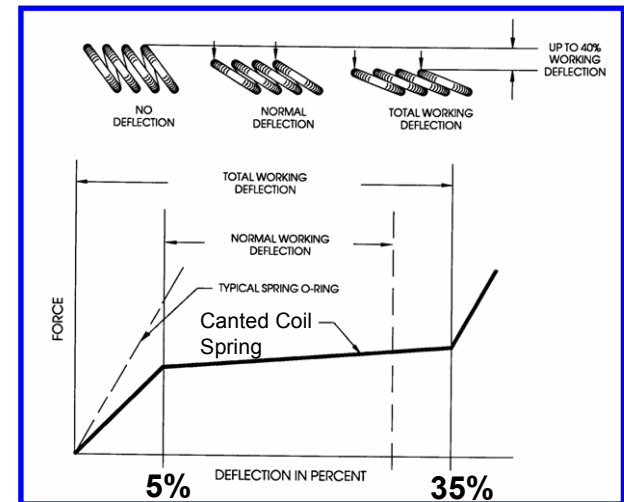
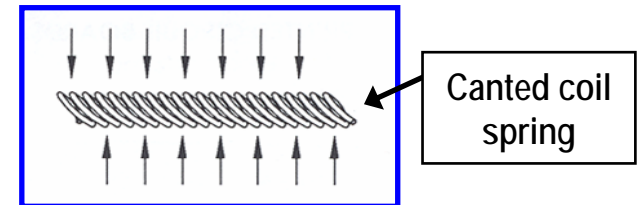
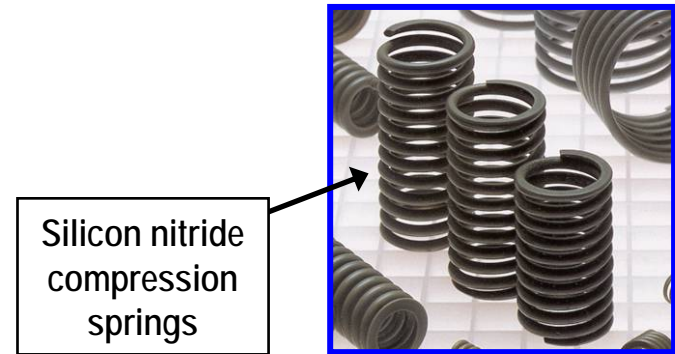


- **Superalloys** – Limited strength/creep beyond 1500°F
- **Refractory Alloys** – Good strength/creep to ~2300°F, poor oxidation resistance
- **Ceramic/CMC** – Good strength/creep >2300°F, limited elasticity



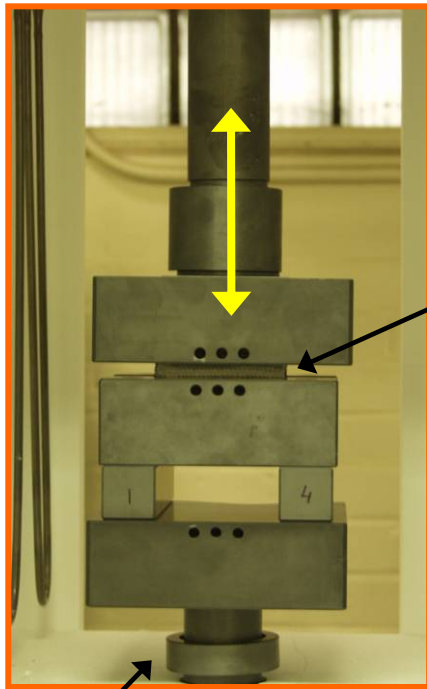
# High Temperature Seal Preloader Development

- Goal: Provide ~0.1-in. stroke to keep seal in contact with sealing surface
- Silicon nitride compression springs
  - Commercially available
  - Potential for high temperature use (2000+°F)
- Examining refractory metal canted coil springs
  - Unique load vs. displacement behavior of canted coil spring provides nearly constant force over large stroke
  - Large working deflection for size
  - Developing springs for high temperature use (2200°F)
    - Work to-date on TZM
    - Considering other refractory alloys
    - Refractory alloys require oxidation resistant coating (e.g., platinum)

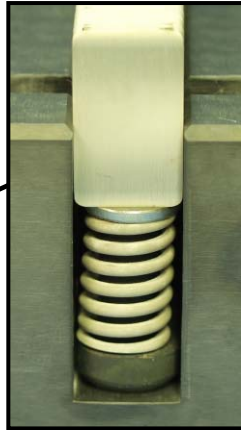


Large working deflection of canted coil spring

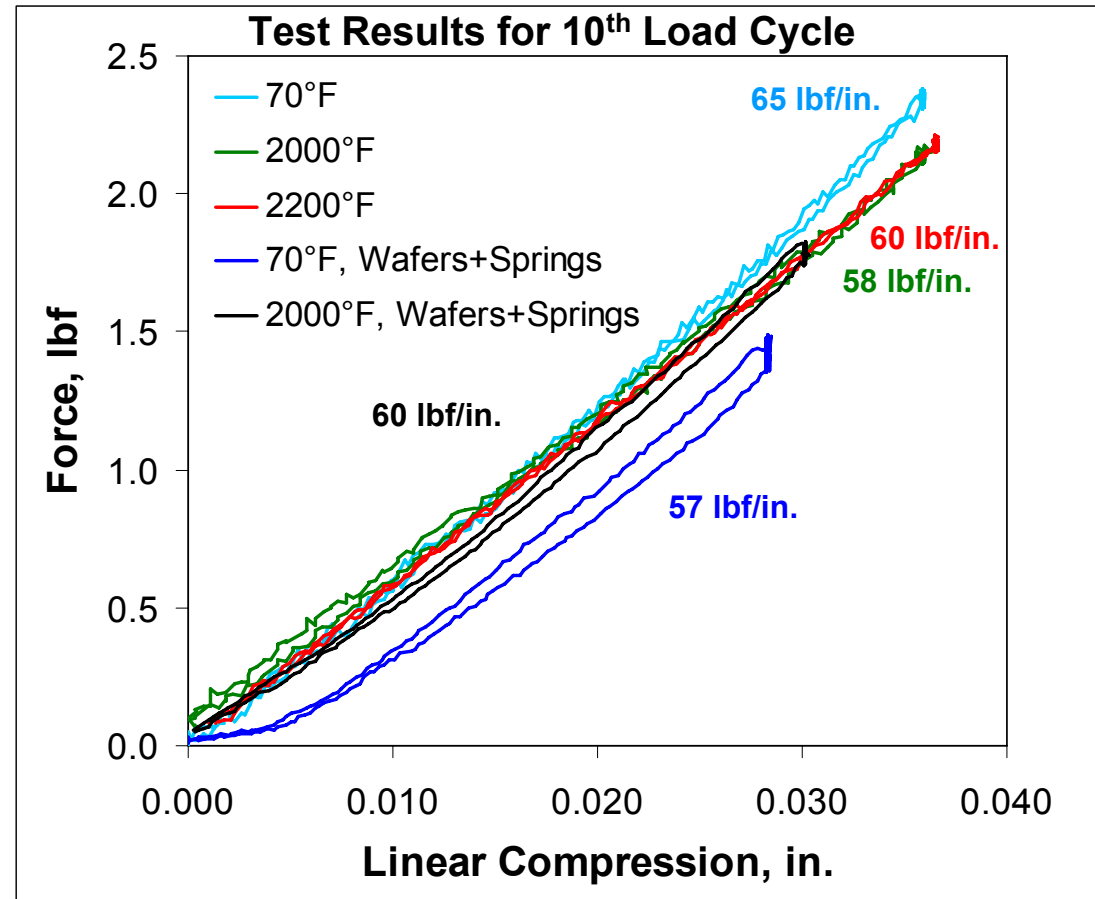
# Compression Test Results on Silicon Nitride Springs



Load cell  
below furnace



\*Note: 4 springs  
tested under  
wafer seals; 1  
spring used for  
other tests

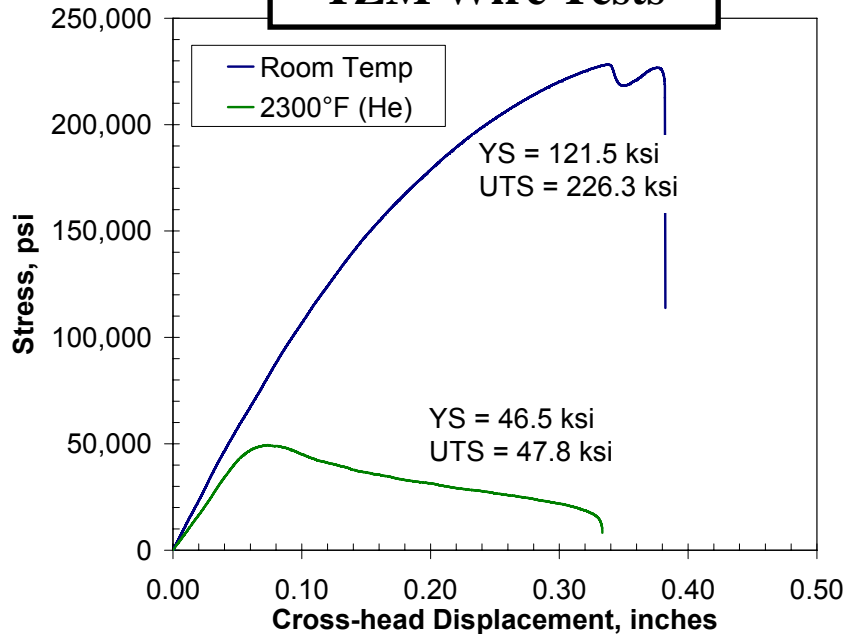


- Multiple load cycles at room temperature, 2000°F & 2200°F
- No permanent set at any temperature even for wafers on top of springs

**Springs show promise as high temperature seal preload devices**

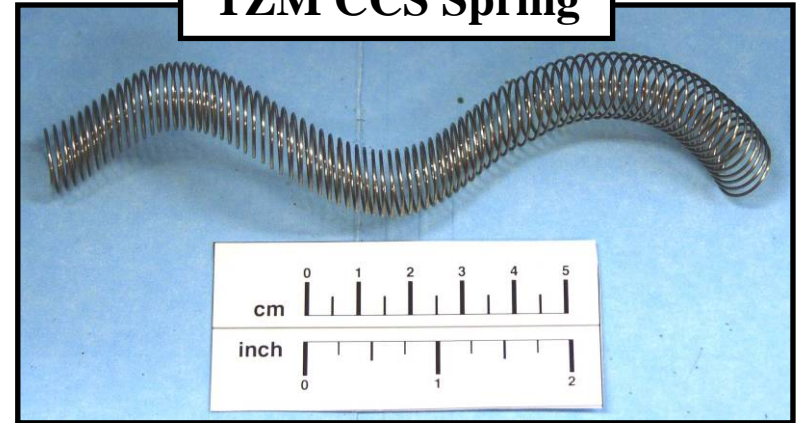
# Advanced Preloaders – High Temperature TZM Canted Coil Spring

**TZM Wire Tests**

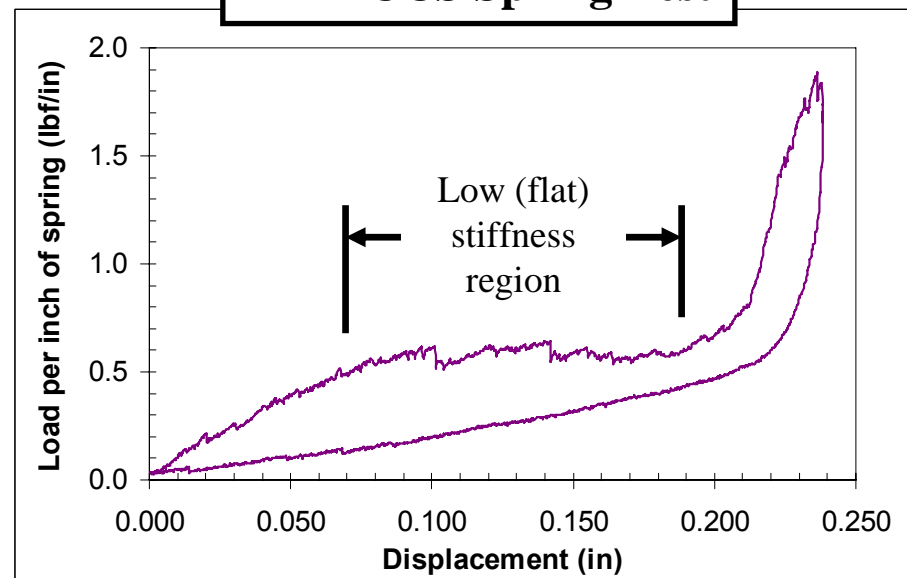


- ✓ TZM wire successfully drawn (2 lots)
- ✓ High temp wire tensile tests completed
  - Far superior spring properties: 46.5 ksi at 2300°F
  - Compare to yield strength of 45 ksi at:
    - ~1500°F for IN X-750
    - ~1700°F for Rene 41
- ✓ Prototype TZM canted coil spring successfully fabricated and tested
- ✓ Pt coating trials in progress

**TZM CCS Spring**



**TZM CCS Spring Test**

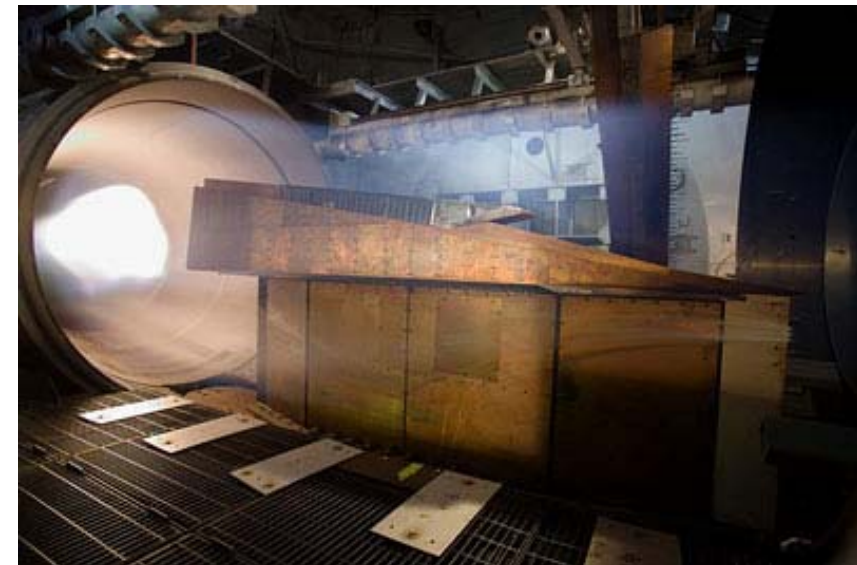


# Summary: Propulsion Seals

- Hypersonic propulsion systems pose significant challenges to seals:
  - Extreme thermal environments require active coolant even for ceramic designs
    - Ceramic and refractory materials being considered for seals and preload systems
  - Weight minimized walls distort requiring flexible seals
  - High acoustic environments
  - Ceramic engine walls pose rough surfaces requiring durable seals for re-use
  - Ram/scramjet engines
    - Without proper design, flow recirculation (“sneak flow”) can occur from higher pressure zones (e.g. combustor) to the inlet through improperly sealed cavities.
    - “Un-start” can momentarily increase pressures multiple fold compared to baseline levels (engine structure and seal integrity)
- NASA GRC continuing to develop advanced seal concepts (within limited funding):
  - Demonstrated silicon nitride wafer seal durability against C/SiC and monolithic SiC through scrub tests up to 2200°F
  - Demonstrated wafer seal leakage rates ~5% of those for best textile seals
  - Demonstrated excellent resiliency of commercially available silicon nitride compression springs at temperatures up to 2200°F
  - Fabricated and tested (at ambient temp.) first known refractory (TZM) canted coil spring

# Future Work

- Continue seal and seal pre-loader development for 2000-2300°F operating temperatures
- Perform sub-system demonstration of seals in a simulated high heat flux, high acoustic environment.
- Perform sub-scale engine tests





# Acknowledgements

- Mr. Cooper Snapp, JSC Engineering for his help providing information on Shuttle seal technology.

# Shuttle References

- Finkbeiner, J.R., Dunlap, P.H., Steinetz, B.M., DeMange, J.J., and Newswander, D.R., 2005, "Investigations of Shuttle Main Landing Gear Door Environmental Seals," NASA/TM-2005-213860, September.
- Snapp, Cooper G. SPACE SHUTTLE ORBITER THERMAL PROTECTION SYSTEM PROCESSING ASSESSMENT 2000 APPENDIX A OVERVIEW OF THE ORBITER THERMAL PROTECTION SYSTEM, Orbiter Engineering Report KLO-00-006 October 17, 2000.
- Cleland, J. and Iannetti F., "Thermal Protection System of the Space Shuttle," NASA Contractor Report 4227, Contract NASW-3841-72, 1989.



# Vehicle/Control Surface Seal References

- Cleland, John., Iannetti, Francesco, 1989, "Thermal Protection System of the Space Shuttle," NASA Contractor Report 4227, Prepared for Off of Commercial Programs, NASA Contract NASW-3841-72.
- DeMange, Jeffrey J, Dunlap, Patrick H. Jr., Steinetz, B.M., Drlik, Gary, 2007, "An Evaluation of High Temperature Airframe Seals for Advanced Hypersonic Vehicles," AIAA-2007-5743 , NASA TM- in process Presented at the 2007 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH.
- DeMange, Jeffrey J., Dunlap, Patrick H. Jr., Steinetz, Bruce M, 2006, "Improved Seals for High Temperature Airframe Applications." Paper Number: AIAA-2006-4935, TM 2006-214465, Presented at the 2006 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Sacramento, CA.
- DeMange, J.J., Dunlap, P.H., Steinetz, B.M., 2004, "Advanced Control Surface Seal Development for Future Space Vehicles," Presentation and Paper at 2003 JANNAF Conference, Dec. 1-5, Colorado Springs, CO. (NASA TM-2004-212898).
- Dunlap, Jr., P. H., Steinetz, Bruce M.; Curry, Donald M.; Newquist, C. W.; Verzemnieks, J.: 2001, "Further Investigations of Control Surface Seals for the X-38 Re-Entry Vehicle," AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2001-3628, Salt Lake City, Utah, July.
- Dunlap, Jr., P. H., Steinetz, Bruce M.; Curry, Donald M.; "Rudder/Fin Seal Investigations for the X-38 Re-Entry Vehicle, 2000," NASA TM-2000-210338; AIAA-2000-3508, Presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Huntsville, AL, July 2000; 2000 NASA Seal/Secondary Air System Workshop Volume 1, pp. 315-330, October 2001.
- Finkbeiner, Josh, Dunlap, Patrick H., Steinetz, Bruce M, DeMange, Jeff, Newswander, Daniel., 2005, "Investigations of Shuttle Main Landing Gear Door Environmental Seals," Presented at the 2005 AIAA/ASME/SAE/ASEE Joint Propulsion conference, Tucson, AZ, AIAA-2005-4155, also NASA/TM—2005-213860
- Finkbeiner, J.R., Dunlap, P.H., Steinetz, B.M., Robbie, M., Baker, F., and Erker, A.: 2004, "On the Development of a Unique Arc Jet Test Apparatus for Control Surface Seal Evaluations. NASA TM-2004-213204, AIAA-2004-3891, August 2004. Presented at the 2004 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2004, Ft. Lauderdale, FL.
- Hoey, Robert, G., X-15 History Conference Presentation Materials:  
[www.hq.nasa.gov/pao/History/x15conf/contrib.html](http://www.hq.nasa.gov/pao/History/x15conf/contrib.html)

# Vehicle/Control Surface Seal References (Cont'd)

- Newquist, C. W., Verzemnieks, J., Keller, P.C., Rorabaugh, M., Shorey, M.W., 2002, "Advanced High Temperature Structural Seals," NASA CR-2002-211973, October, 2002, (thermal barrier development and arc jet test results).
- Oswald, Jay J, Mullen, Robert L., Dunlap Patrick H., Steinetz Bruce M, 2005, "Modeling of Canted Coil Springs and Knitted Spring Tubes as High Temperature Seal Preload Devices," Presented at the 2005 AIAA/ASME/SAE/ASEE Joint Propulsion conference, Tucson, AZ, AIAA-2005-4156
- Oswald, J.J., Mullen, R.H., Dunlap, P.H., and Steinetz, B.M.: 2004, "Modeling and Evaluation of High Temperature Canted Coil Springs as Seal Preloading Devices." NASA TM-2004-213189, AIAA-2004-3889, August 2004. Presented at the 2004 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2004, Ft. Lauderdale, FL.
- Snapp, Cooper, Gordon, Mike, 2000, "Space Shuttle Orbiter Thermal Protection System Processing Assessment, 2000, Appendix A, Overview of the Orbiter Thermal Protection System." Report No. KLO-00-006, October, 2000.
- Taylor, S.C., DeMange, J.J., Dunlap, Jr., P.H., Steinetz, B.M., 2005, "Further Investigations of High Temperature Knitted Spring Tubes for Advanced Control Surface Seal Applications," AIAA-2005-4154, presented at the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, AZ, July 10-13.
- Taylor, S.C., DeMange, J.J., Dunlap, P.H., Steinetz, B.M., 2004, "Evaluation of High Temperature Knitted Spring Tubes for Structural Seal Applications," NASA TM-2004-213183, AIAA-2004-3890. Presented at the 2004 AIAA/ASME/SAE/ASEE conference, July, 2004, Ft. Lauderdale, FL.

# Propulsion Seal References

- Cai, Zhong; Mutharasan, Rajakkannu; Ko, Frank.; Steinetz, Bruce M.: 1994, "Development of Braided Fiber Engine Seals", J. of Advanced Materials, Vol. 25, No. 2, pp. 29-35, January.
- Cai, Zhong; Mutharasan, Rajakkannu; Ko, Frank K.; Steinetz, Bruce M.: 1994, "Development of hypersonic engine seals - Flow effects of preload and engine pressures," 29th AIAA/SAE/ASME/ASEE, Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993, AIAA Paper 93-1998, Journal of Propulsion and Power, vol. 10, no. 6, November-December 1994, pp. 884-889.
- Cai, Zhong; Steinetz, Bruce M.: 1994, "Numerical Simulation on the Leakage Flow of Textile Engine Seals", Society for the Advancement of Material and Process Engineering, Vol. 26, pp. 14-24, October 17-20.
- Cai, Zhong; Mutharasan, Rajakkannu; Ko, Frank; Steinetz, Bruce M.: 1994, "Parametric Study of Leakage Flow in Braided Fiber Seals," Textile Research Journal, Vol. 64, No. 5, pp. 280-290, May.
- Cai, Zhong; Mutharasan, Rajakkannu; Ko, Frank K; Steinetz, Bruce, M.: 1993, "Development of Hypersonic Engine Seals: Flow Effects of Preload and Engine Pressures," presented at AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, AIAA-93-1998. Journal of Propulsion and Power, Vol. 10, No.6, June 1993, also NASA TM-106333, April.
- Cai, Zhong; Mutharasan, Rajakkannu; Ko, Frank; Du, Guang-Wu, Steinetz, Bruce M.: 1993, "Development of Braided Fiber Seals for Engine Applications," NASA CP-3211, 1993, Fiber-Tex 1992, proceedings of the 6th Conference on Advanced Engineering Fibers and Textile Structures for Composites, October 1992, Philadelphia, PA.





# Propulsion Seal References

- DellaCorte, Christopher D.; Lukaszewisz, Victor; Morris, D. E.; Steinetz, Bruce M.: 1994, "Static and Dynamic Friction Behavior of Candidate High Temperature Airframe Seal Materials," NASA TM-106571, December.
- DellaCorte, Christopher; Steinetz, Bruce M.: 1994, "Tribological Comparison and Design Selection of High-Temperature Candidate Ceramic Fiber Seal Materials," Lubrication Engineering, Vol. 50, No. 6, pp. 469-477, June.
- DellaCorte, Christopher D.; Steinetz, Bruce M.: 1993, "Sliding Durability of Two Carbide-Oxide Candidate High Temperature Fiber Seal Materials in Air to 900°C," NASA TM-105554, April.
- DellaCorte, Christopher D.; Steinetz, Bruce M.: 1993, "Relative Sliding Durability of Two Candidate High-Temperature Oxide Fiber Seal Materials," Journal of Propulsion and Power, Vol. 9, No. 2, March-April, 1993, pp. 307-312, NASA TM-105199, pp. 18, 1991.
- DellaCorte, Christopher; Steinetz, Bruce M.: 1992a, "Relative Sliding Durability of Candidate High Temperature Fiberseal Materials," NASA TM-105806, August.
- DellaCorte, Christopher D.; Steinetz, Bruce M.: 1992b "Relative Sliding Durability of Two Candidate High-Temperature Oxide Fiber Seal Materials", AIAA-92-3713, July.
- DellaCorte, Christopher; Steinetz, Bruce M.: 1992c, "Tribological Evaluation of an Al<sub>2</sub>O<sub>3</sub> – SiO<sub>2</sub> Ceramic Fiber Candidate for High Temperature Sliding Seals", STLE Tribology Transactions, Vol. 37, No. 2, pp. 369-377, April 1994, NASA TM-105611, pp 18, April 1992.
- DellaCorte, Christopher D.; Steinetz, Bruce M.: 1992d, "Sliding Durability of Candidate Seal Fiber Materials in Hydrogen from 25 to 900°C," NASA TM-105939, January 1992, International Conference of Wear of Materials, January .
- DellaCorte, Christopher D.; Steinetz, Bruce M.: 1991, "Relative Sliding Durability of Two Candidate High Temperature Oxide Fiber Seal Materials", NASA TM-105199, September.
- DellaCorte, Christopher D.; Steinetz, Bruce M.; Brindley, Pamela M.: 1990, "Tribological Properties of Ceramic (Ti<sub>3</sub>Al-Nb) Sliding Couples for Use as Candidate Seal Materials to 700°C", Surface & Coatings Technology, Vol. 43-44, pp. 663-673, December 1990, NASA TM pp. 19, 1990.
- DellaCorte, Christopher D.; Steinetz, Bruce M.; Brindley, Pamela M.: 1990, "Tribological Properties of Ceramic (Ti<sub>3</sub>Al-Nb) Sliding Couples for Use as Candidate Seal Materials to 700°C", NASA TM-102401, January 1989, Surface & Coatings Technology, Vol. 44, No. 1-3, December 1990, International Conference on Metallurgical Coatings and 8th International Conference on Thin Films, April 1990, San Diego, CA, Elsevier Applied Science, 1990, pp. 663-673.

# Propulsion Seal References (Cont'd)

- Dunlap, P.H., Steinetz, B.M., and DeMange, J.J.: 2004, "Further Investigations of Hypersonic Engine Seals." NASA TM-2004-213188, AIAA-2004-3887, August 2004. Presented at the 2004 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2004, Ft. Lauderdale, FL.
- Dunlap, P.H., Steinetz, B.M., DeMange, J.J., 2004, "High Temperature Propulsion System Structural Seals for Future Space Launch Vehicles," Presentation and Paper at 2003 JANNAF Conference, Dec. 1-5, Colorado Springs, CO. (NASA TM-2004-212907).
- Dunlap, P.H., Steinetz, B.M., DeMange, J.J., 2003, "Toward an Improved Hypersonic Engine Seal" NASA TM-2003-212531, AIAA-2003-4834, Presented at the 2003 AIAA/ASME/SAE/ASEE conference, July, 2003, Huntsville, AL.
- Dunlap, P.H. Steinetz, B.M., Curry, D.M. DeMange, J.J., Rivers, H.K., Hsu, S., "Investigations of Control Surface Seals For Re-Entry Vehicles," *Journal of Spacecraft and Rockets*, Vol 40, No. 4, NASA TM-2002-211708, also AIAA-2002-3941, Presented at the 2002 AIAA/ASME/SAE/ASEE conference, July, 2002, Indianapolis, IN.
- Hung, F.T. and Scottoline, C.A., 1975, "Aerodynamic Heating in Gaps in the Presence of Protuberances and Shock Wave Impingement," AIAA Paper 75-670.
- Ko, Frank K.; Cai, Zhong; Mutharasan, Rajakkannu; Steinetz, Bruce M.: 1994, "Development of Braided Rope Engine Seals," published in *SAMPE Journal of Advanced Materials*, Vol. 25, No. 2, January 1994, also NASA TM-105902, February 1994.
- Miller, Jeffrey H.; Steinetz, Bruce M.; Sirocky, Paul J.; Kren, Lawrence A.: 1988, "Hot Dynamic Test Rig for Measuring Hypersonic Engine Seal Flow and Durability," NASA TM-106507, February 1994, *J. of Propulsion and Power*, Vol. 10, No 5, September-October 1994, pp 716-720. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 34th and AIAA/ASME Adaptive Structures Forum, La Jolla, CA, April, 1993, Technical Papers. Pt. 1, p. 445-453.
- Miller, Jeffrey H.; Steinetz, Bruce M.; Sirocky, Paul J.; Kren, Lawrence A.: 1993, "A Hot Dynamic Seal Rig for Measuring Hypersonic Engine Seal Durability and Flow Performance." *AIAA Journal of Propulsion and Power*, Vol. 10, No. 5, pp. 716-720, AIAA 93-1346, January 1993, NASA TM-106294, April.
- Mutharasan, Rajakkannu; Steinetz, Bruce M.; Tao, Xiaoming; Du, Guang-Wu; and Ko, Frank K.: "Development of Braided Rope Seals for Hypersonic Engine Applications: Flow Modeling," *AIAA Journal of Propulsion and Power*, Vol. 9, No. 3, pp. 456-461, June 1993, NASA TM-105942, December 1992, AIAA-91-2495, June 1991.
- Mutharasan, Rajakkannu; Steinetz, Bruce M.; Tao, Xiaoming; Ko, Frank: 1991, "Development of Braided Rope Seals for Hypersonic Engine Applications Part II: Flow Modeling," NASA TM-104371, June 1991, presented at the AIAA, SAE, ASME & ASEE, Joint Propulsion Conference, Philadelphia, PA, AIAA 91-2495.
- Oswald, Jay J, Mullen, Robert L., Dunlap Patrick H., Steinetz Bruce M, 2005, "Modeling of Canted Coil Springs and Knitted Spring Tubes as High Temperature Seal Preload Devices," Presented at the 2005 AIAA/ASME/SAE/ASEE Joint Propulsion conference, Tucson, AZ, AIAA-2005-4156
- Oswald, J.J., Mullen, R.H., Dunlap, P.H., and Steinetz, B.M.: 2004, "Modeling and Evaluation of High Temperature Canted Coil Springs as Seal Preloading Devices." NASA TM-2004-213189, AIAA-2004-3889, August 2004. Presented at the 2004 AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2004, Ft. Lauderdale, FL.
- Steinetz, Bruce M., Dunlap, Patrick H., 2003, "High Temperature Seal for Large Structural Movements," LEW 17,112-1, US Patent No. 6,702,300 Issued on 3/9/2003.



# Propulsion Seal References (Cont'd)

- Steinetz, Bruce M.; Adams, Michael L, 1998: "Effects of Compression, Staging, and Braid Angle on Braided Rope Seal Performance," J. of Propulsion and Power, Vol. 14, No. 6, pp. 934-940, December. See also 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-97-2872, Seattle, Washington, July 1997, NASA TM, Vol. 107504, July 1997.
- Steinetz, Bruce M.; Hendricks, Robert C.: 1997, "Aircraft Engine Seals," Chapter 9 of Tribology for Aerospace Applications, STLE Special Publication SP-37, 1997.
- Steinetz, Bruce M.; Adams, Michael L.; Bartolotta, Paul A.; Darolia, Ram; Olsen, Andrew: 1996, "High-Temperature Braided Rope Seals for Static Sealing Applications", AIAA, ASME, SAE, and ASEE, Joint Propulsion Conference and Exhibit, 32nd, Lake Buena Vista, FL, July 1-3, 1996, AIAA 96-2910, Journal of Propulsion and Power, October 1997, Vol. 13, No. 5, pp. 675-682, NASA TM 107233, July.
- Steinetz, Bruce M.; Kren, Lawrence A.: "Resilient Braided Rope Seal," US-Patent-Appl-SN-739342, October 1996; US-Patent-6,039,325 FD: 9 April 1998.
- Steinetz, Bruce M.; Kren, Lawrence A.; Cai, Zhong: 1994, "High Temperature Flow and Sliding Durability Assessments of Hypersonic Engine Seals," NASA TP-3483, 1994.
- Steinetz, Bruce M.; Sirocky, Paul J.: 1993, "High-temperature, Bellows Hybrid Seal," US-PATENT-5,332,239, January.
- Steinetz, Bruce M.; DellaCorte, Christopher D.; Kren, Lawrence A.; Sirocky, Paul J.: 1993, "High Temperature Hypersonic Engine Seal Technology Development: Solid Seal/Material Evaluation," presented as paper No. 114 at the 1993 National Aerospace Plane Mid-Term Technology Review, Monterey, CA, April 1993, published in NASP CP-12080, Vol. 6, Structures, 1993
- Steinetz, Bruce M.; Sirocky, Paul J.: 1992, "Dynamic, High-Temperature, Flexible Seal," NASA Tech Brief, Vol 16, P. 71, March 1992.
- Steinetz, Bruce M.: 1992, "Evaluation of an Innovative High Temperature Ceramic Wafer Seal for Hypersonic Engine Applications," NASA TM-105556, February.
- Steinetz, Bruce M.; DellaCorte, Christopher D.; Machinchick, Michael; Mutharasan, Rajakkannu; Du, Guang-Wu; Ko, Frank K.; Sirocky, Paul J.; Miller, Jeffrey H.: 1992, "High Temperature Dynamic Engine Seal Technology Development," presented at the National Aerospace Plane Mid-Term Technology Review, April 1992. NASA TM-105641, January 1992.
- Steinetz, Bruce M.; Mutharasan, Rajakkannu; Du, Guang-Wu; Miller, Jeffrey J.; Ko, Frank K.: 1992, "Engine Panel Seals for Hypersonic Engine Applications: High Temperature Leakage Assessments and Flow Modeling", NASA TM-105260, April 1992, International Symposium on transport Phenomena & Dynamics of Rotating Machinery, pp. 530-541, January .

# Propulsion Seal References (Cont'd)

- Steinetz, Bruce M.; DellaCorte, Christopher D.; Tong, Michael T.: 1991, "High Temperature NASP Engine Seals: A Technology Review", NASA TM-104468, August.
- Steinetz, Bruce M.: 1991, "Evaluation and Ranking of Candidate Ceramic Wafer Engine Seal Materials", NASA TM-103795, May.
- Steinetz, Bruce M.; DellaCorte, Christopher D.; Tong, Michael T.: 1991, "High Temperature NASP Engine Seals: A Technology Review", presented at the 10th National Aerospace Technology Symposium, Monterey, California, April, 1991, NASA TM-104468.
- Steinetz, Bruce M.: 1991, "National Aerospace Plane Engine Seals: High Temperature Seal Performance Evaluation", published in NASA CP-10070, Seal Flow Code Development, pp. 165-170, March.
- Steinetz, Bruce M.; Melis, Matthew E.; Test, Mark G.; Orletski, Dirk: 1991, "High Temperature NASP Engine Seal Development", NASA TM-103716, February.
- Steinetz, Bruce M.; Sirocky, Paul J.: 1991, "High Temperature, Flexible, Thermal Barrier Seal", patent application, NASA-CASE-LEW-14672-1, November 1989. Pat. No. 5,014,917, May 14, 1991.
- Steinetz, Bruce M.: 1991, "High Temperature Performance Evaluation of a Hypersonic Engine Ceramic Wafer Seal." NASA TM-103737, April.
- Steinetz, Bruce M.: "A Test Fixture for Measuring High Temperature Hypersonic-Engine Seal Performance," NASA TM-103658, December 1990.
- Steinetz, Bruce M.; Sirocky, Paul J.: "High Temperature Flexible, Fiber-Preform Seal", NASA LEW-15085, August 1989. Pat. No. 5,082,293, January 1992.
- Steinetz, Bruce M.; Melis, Matthew E.; Test, Mark G.: 1990, "High Temperature NASP Engine Seal Development (U)", Presented at the 9th National Aerospace Plane Technology Symposium, published in NASA CP-9057, Vol VI, Structures, December 1990.
- Steinetz, Bruce M.; Sirocky, Paul J.: 1990, "High Temperature Flexible Seal", NASA-CASE-LEW-14695, December 1988. Pat. No. 4,917,302, April 17, 1990
- Steinetz, Bruce M.; Sirocky, Paul J.: 1989, "High Temperature, Flexible, Pressure-Actuated Brush Seal", NASA LEW-15086, August 1989. Pat. No. 5,076,590, December 1991, NASA Tech Briefs vol: 17 Iss: 2, p. 74.



# Propulsion Seal References (Cont'd)

- Steinetz, Bruce M.; DellaCorte, Christopher D.; Tong, Michael T.: 1989, "Seal Concept and Material Performance Evaluation for the NASP Engine", presented at the 7th National Aerospace Plane Technology Symposium, published in NASA CP-7045, Vol. VI, Structures, November 1989, pp. 39-58.
- Steinetz, Bruce M.; Tong, Michael T.; Coirier, William J.: 1989, "Seal Thermal Analysis of Panel-Edge Seals for Hypersonic Engines", presented at 6th National Aerospace Plane Technology Symposium, NASA CP-6039, Vol. VI, Structures, May.
- Steinetz, Bruce M.; Sirocky, Paul J.: 1989, "Dynamic, High-Temperature, Flexible Seal," NASA Tech Brief, Vol 13, P. 101, April.
- Steinetz, Bruce M.: 1988, "Status of Seal Development for Hypersonic Applications", presented at 5th National Aerospace Plane Technology Symposium, NASA CP-5033, Vol. VI, Structures, November 1988.
- Steinetz, Bruce M.: 1986, "Seals Concepts and Testing for Hypersonic Propulsion Structures", presented at 2nd National Aerospace Plane Technology Symposium, November 1986, NASA CP-2014, Vol. VI, Structures.
- Tong, Michael T.; Steinetz, Bruce M.: 1991, "Thermal and Structural Assessments of a Ceramic Wafer Seal in Hypersonic Engines", presented at the 27th Joint Propulsion Conference cosponsored by the AIAA, ASME, SAE, and ASEE, Sacramento, California, June 24-17, 1991, AIAA-91-2494, June 1991, NASA TM 103651, January.



# Solid Rocket (5500°F) Motor Thermal Barrier Seal References

- Steinetz, Bruce M.; Dunlap, Patrick H.; Phelps, Jack, Bauer, Paul; Bond, Bruce: 2002, "Thermal Barrier/Seal for Extreme Temperature Applications," NAS8-97238, January.
- Steinetz, Bruce M., Dunlap, Patrick H. 2002, "Rocket Motor Joint Construction Including Thermal Barrier," U.S. Patent No. 6,446,979 B1, Issue Date: September 10, 2002, LEW 16,684-1.
- Steinetz, Bruce M.; Dunlap, Jr., Patrick H.: 2000, "Feasibility Assessment of Thermal Barriers for Extreme Transient Temperatures" Journal of Propulsion and Power, Vol. 16, Number 2, pp. 347-356, March-April 2000, NASA TM-1998-208484.
- Steinetz, Bruce M.; Dunlap, Patrick H.: "Development of Thermal Barriers for Solid Rocket Motor Nozzle Joints" NASA-TM-1999-209191, June 1999. Journal of Propulsion and Power, Vol. 17 No. 5, pp. 1023-1034 September/October 2001.
- Steinetz, Bruce M.; Dunlap, Patrick H.: 2000, "Development of Thermal Barriers for Solid Rocket Motor Nozzle Joints" 1999 NASA Seal/Secondary Air System Workshop, Vol. 1, pp. 299-315 October 2000.
- Steinetz, Bruce M.; Dunlap, Patrick H.: 1999, "Development of Thermal Barriers for Solid Rocket Motor Nozzle Joints" NASA TM-1999-209278, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-99-2823, Los Angeles, CA, June.
- Steinetz, Bruce M.; Dunlap, Patrick H.: 1999, "Feasibility Assessment of Thermal Barriers for Shuttle RSRM Nozzle Joint Locations" presented at the Seals/Secondary Flows Workshop, October 1998, Cleveland, OH, NASA CP1999-208916/Vol. 1, July.
- Steinetz, Bruce M.; Dunlap, Patrick H.: "Flexibility Assessment of Thermal Barrier Seals for Extreme Transient Temperatures," 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 98-3288, Cleveland, Ohio, July 1998

# **Appendix A**

## **Vehicle Seals**

# Thermal Barrier Sizing Tool

## Initial Sizing, Room Temperature

Initial Gap (in)	Initial Seal height (in)	Initial % Compression	Final % Compression after +/- Gap change			
			Gap Change (in)			
			+0.050	-0.050	+0.100	-0.100
0.25	0.375	33	20	47	7	60
	0.500	50	40	60	30	70
	0.625	60	52	68	44	76
0.30	0.375	20	7	33	-7	47
	0.500	40	30	50	20	60
	0.625	52	44	60	36	68
0.35	0.375	7	-7	20	-20	33
	0.500	30	20	40	10	50
	0.625	44	36	52	28	60
0.50	0.625	20	12	28	4	36
	1.000	50	45	55	40	60
	1.25	60	56	64	52	68

### Design Guideline

Stay above 10% compression

Stay below 60% compression

yellow highlight Acceptable initial design (at room temperature)

### Gap Change Sign Convention

"+" = gap opening relative to initial gap

"-" = gap closing relative to initial gap

### % Compression with +/- Gap change

Negative Cell

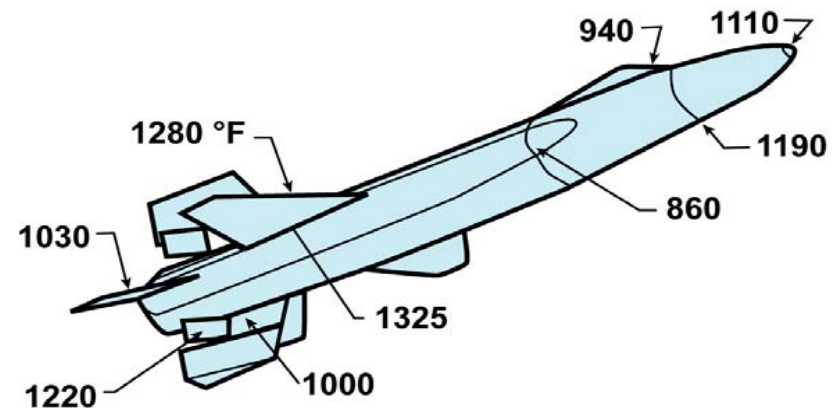
Indicates seal loses contact with sidewall

- Table provides initial design guidance on thermal barrier sizing for different initial gaps and candidate gap changes.

# X-15 Control Surfaces

For flight in the atmosphere, the X-15s used conventional aerodynamic controls consisting of

- Rudders on two wedge-shaped vertical stabilizers controlling yaw movement: top and bottom of fuselage
- Canted horizontal surfaces on the tail controlled pitch when moved in the same direction, and roll when moved differentially.
- When the landing skids were down, the lower vertical tail extended below the skids and was dropped by parachute just before landing.
- Large flaps on main trapezoid wing provide additional lift during glide.



Measured temperatures in flight at Mach 5

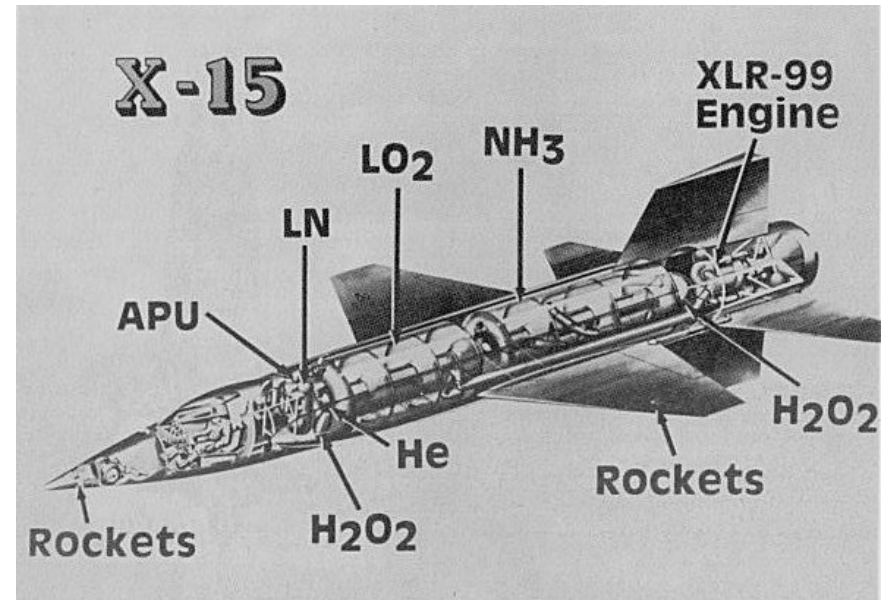
# X-15 Hydraulic Seal Experience

The first challenge that surfaced was the basic X-15 mission and the temperature effects on

- Hydraulic fluid
- "O" ring seals.

After considerable work with the industry and an intensive testing of various candidate products, Oronite 8515 was selected for the O-rings.

- Selected O-ring features
  - Material performed well at high temperatures,
  - Material exhibited greatly reduced "O" ring swelling.
  - These two characteristics were a major step forward in obtaining an excellent system.



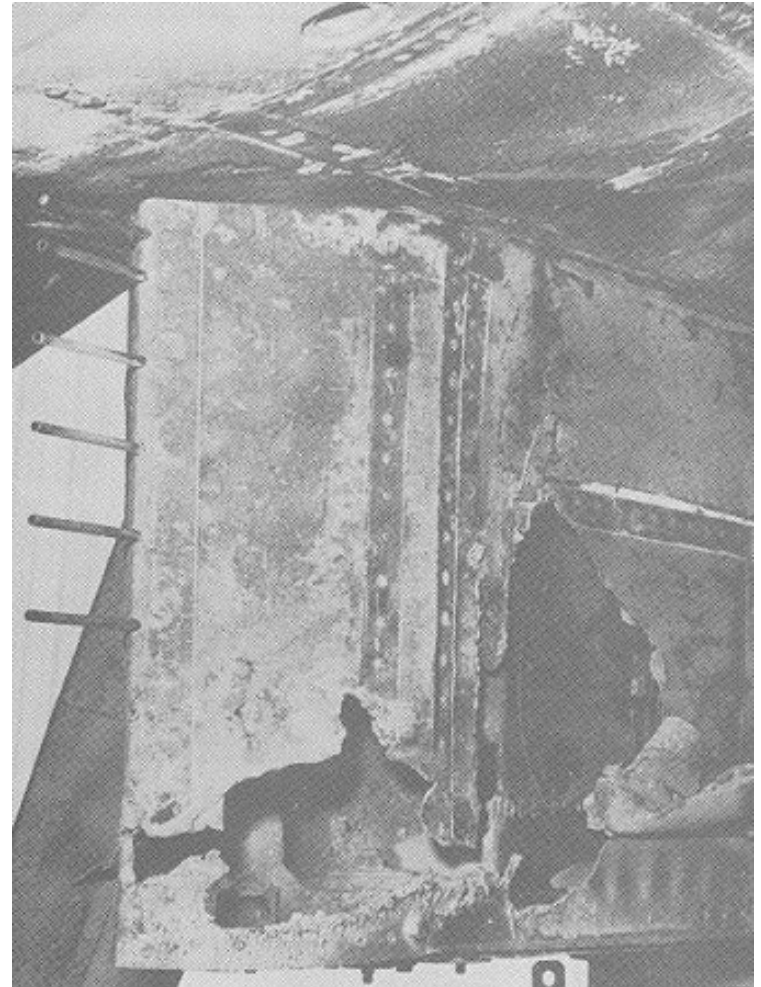
**X-15 Subsystem Diagram**

# X-15 Pylon Experience

The severe damage to the pylon (see fig.) that occurred on the flight to Mach= 6.7 was the result of local shock interference.

Lessons included the following:

- Aerodynamic heating problems tend to be localized effects and are often difficult to predict before flight.
- They also tend to be self-propagating. Although the X-15 was heavily instrumented, none of the aerothermo events described was evident from the instrumentation, real time or otherwise.
- The nature of an X-15 flight was that it was highly transient and the flight time at each new Mach condition was momentary.
- Each of the events described would have been much more severe if the flight condition had been sustained even for a few more seconds .



**Pylon heat damage, left side.**



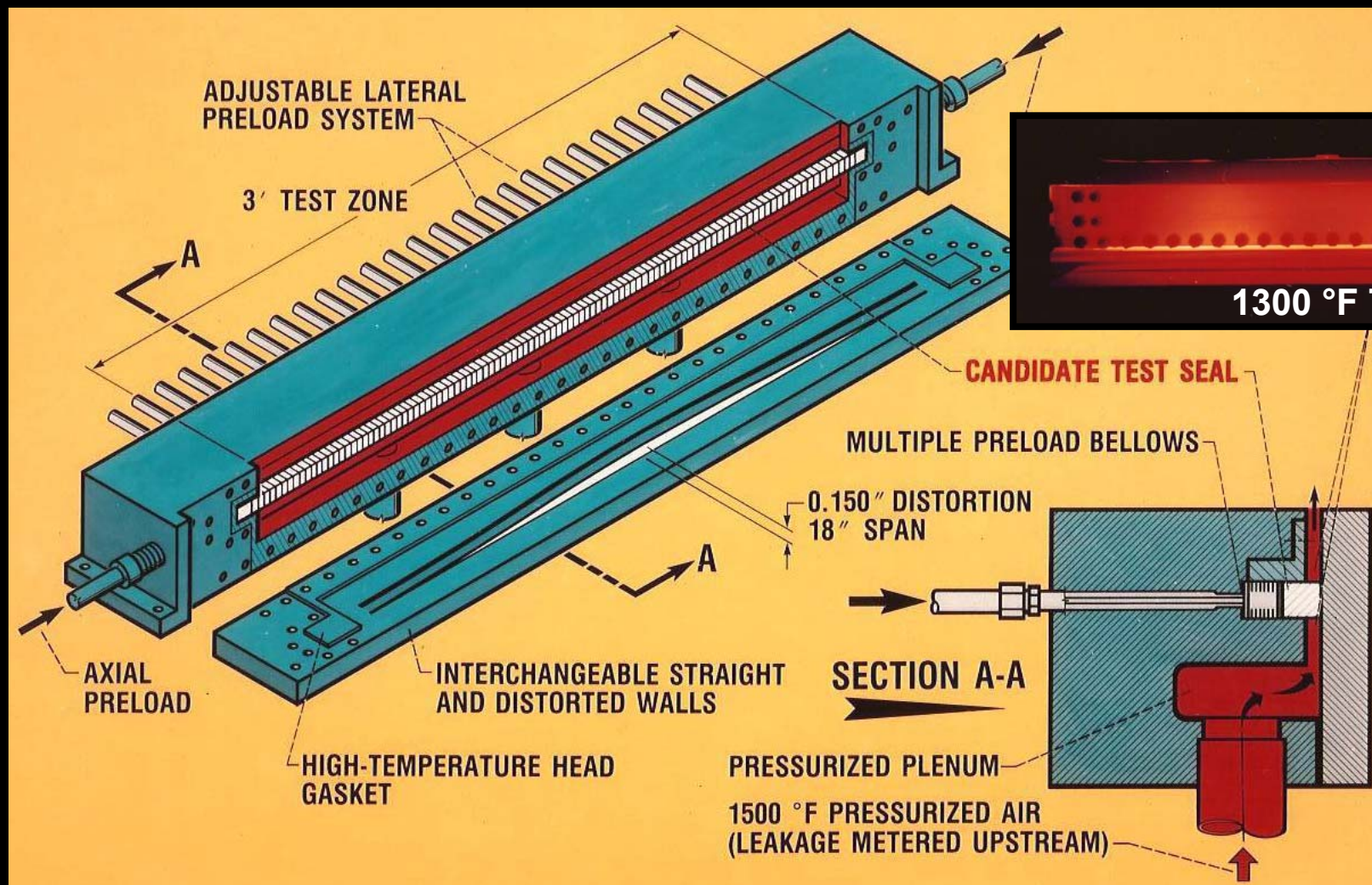
# X-15 Reference Material

- <http://www.dfrc.nasa.gov/Gallery/Movie/X-15/HTML/EM-0033-17.html>
- Above link is a Quicktime movie that details the damage the X-15 sustained after Mach 6.7 flight. At the beginning of the movie you will see what looks to be damage to the wing (melted) leading edge. Toward the end of the movie you will see the lower vertical fin with sidewall damage.

# **Appendix B**

## **Propulsion Seals**

# High Temperature Static Flow Test Fixture



## Features

- Temperature: 1300+°F, Pressure: 0-100 psi
- Leakage measurement

- Nominal 0.5" high seals
- Flat or distorted sidewalls

# Ambient Scrub & Flow Testing Rig Overview

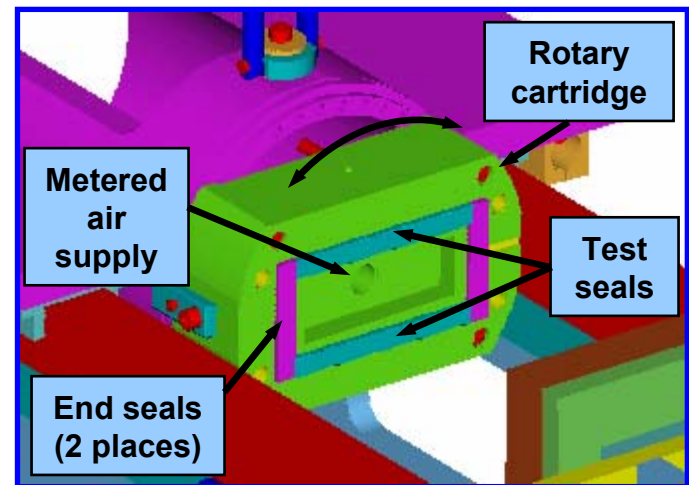
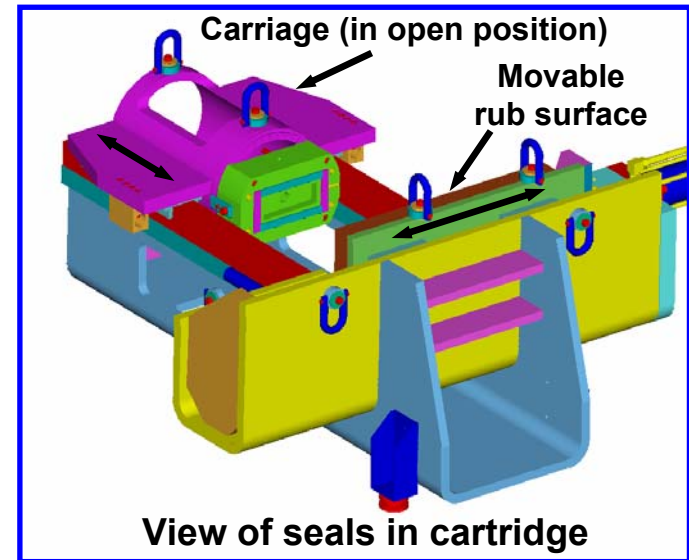
## Purpose

Combined seal flow and scrub tests will be performed in new ambient test rig. Flow rates through seals will be measured for various test conditions:

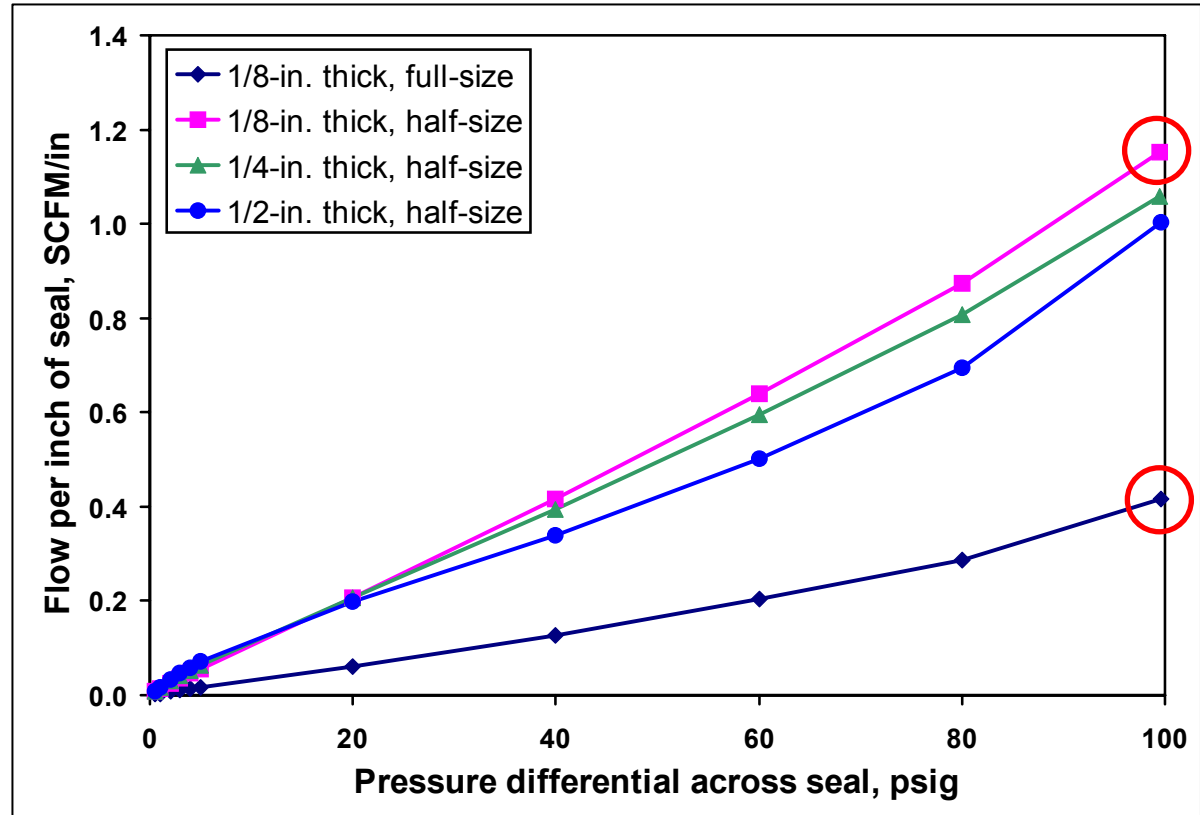
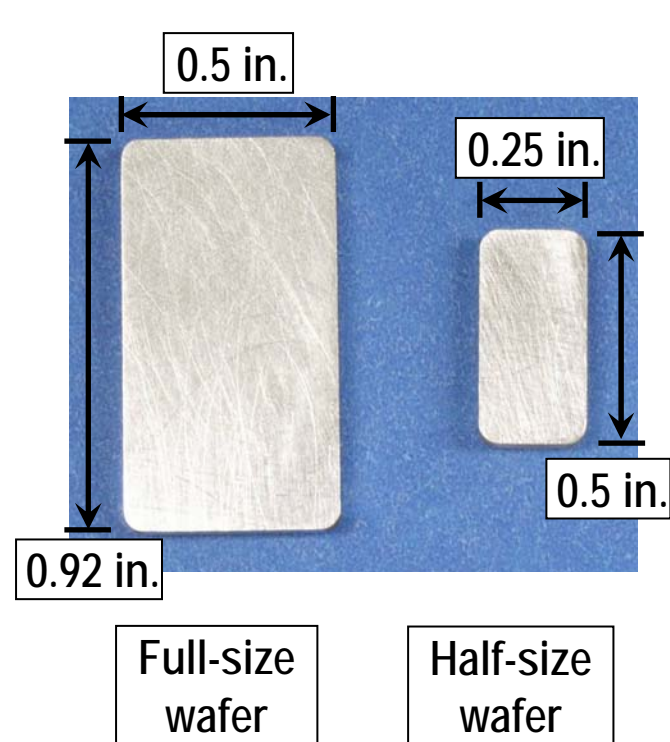
- Scrub/cycle damage
- Compression level
- Gap size
- Rub surface conditions (material, surface roughness, surface profile)
- Scrub direction (e.g., transverse vs. wiping)

## Test Rig Status:

- Fabrication Complete
- Awaiting project funds to complete set-up and test.



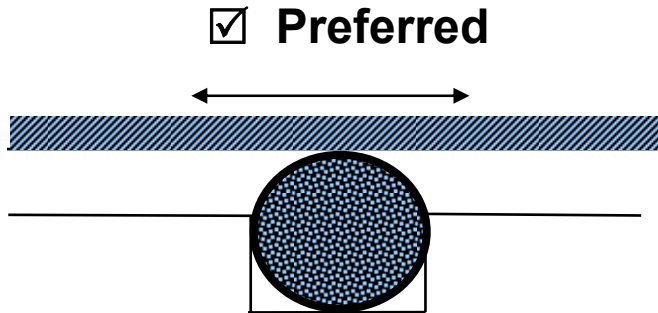
# Wafer Geometry Study: Full-Size vs. Half-Size Wafers



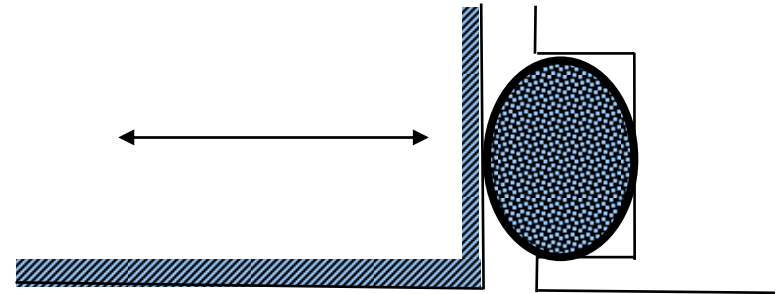
- **Motivation:** Smaller wafers occupy less space, weigh less, fit in tighter locations
  - Flow rates for half-size wafers ~3x those for full-size wafers (1/8-in. thick)
  - Flow rates for half-size wafers 1/10 of those for best textile-based seals
- Can reduce part count 4X for half-size wafers by using 1/2-in. thick wafers vs. 1/8-in. thick (similar flow rates)

# Braided Rope Seal Resiliency: Mounting arrangement for best success

**Relative Sliding  
(piston ring analog)**



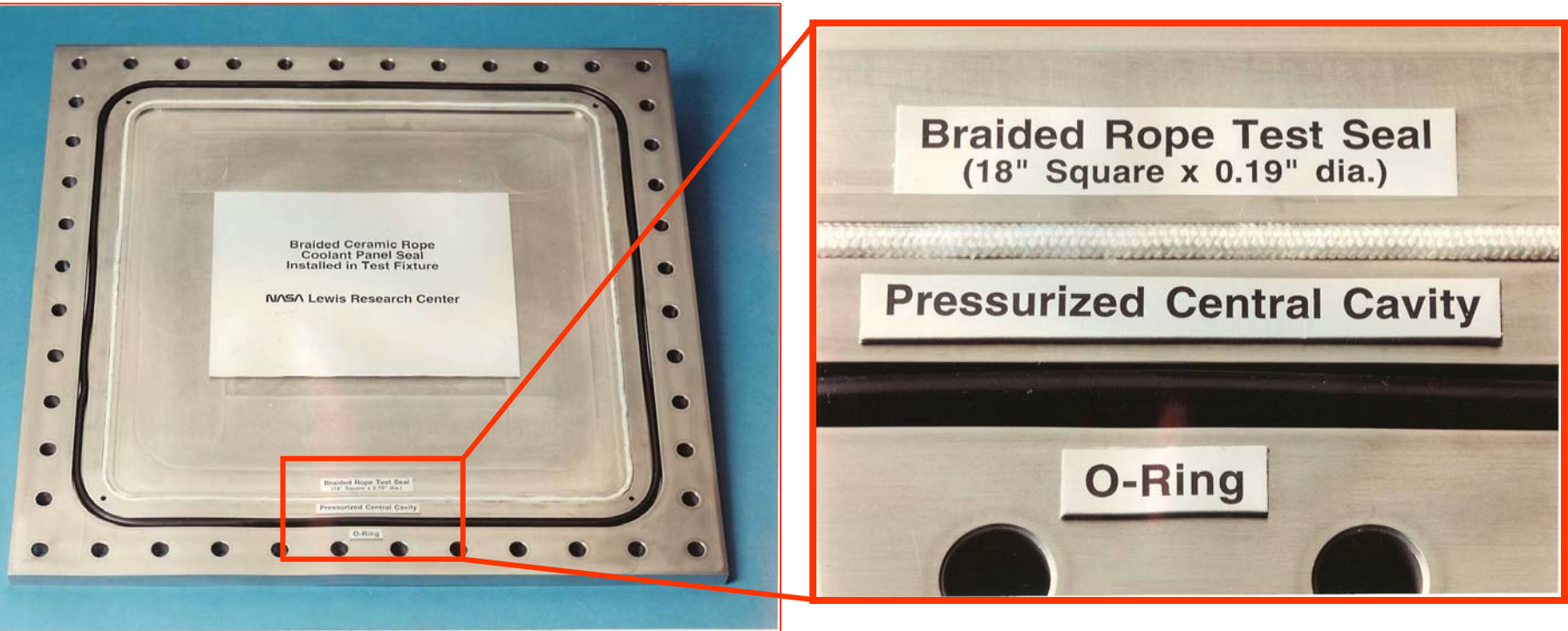
**Gap Opening/Closing  
(face seal analog)**



- Braided rope seals have limited resiliency
  - Best to orient seal so movement is in relative sliding: Piston ring analog
  - If possible, rearrange joint to avoid openings/closings in face seal arrangement



# Continuous Loop Braided Ceramic Rope Seal



- Continuous loop rope seals were produced during the NASP project for candidate high temperature (2000+F) heat exchanger static seals using special split braiding machine.
  - Leakage exceeded flow requirements